Universitat Politècnica de València
Escuela Técnica Superior de Ingeniería de Edificación
Camino de Vera Valencia

Master of Science in Engineering Technology: Construction

Study of the acoustic conditioning of the Aula Magna of the Faculty of Law of the Universitat de València. Analysis of the current situation and a proposal for improvement.

Promotor: Prof. dr. arch. Jaime Llinares Millán

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Phebe Van de Heyning

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Preface

This thesis would not have been written without the help of my promotor prof. dr. arch. Jaime Llinares Millán. I want to thank him for the insights he gave me into room acoustics and for the time he spent with me and the other thesis students to explain the specifics of room acoustics and the software.

I want to thank everyone who made it possible for me to write my thesis during my Erasmus+ program. It was very interesting to study in another country. Studying in Valencia was a unique experience and I learned a lot about being independent and living in the moment. UPV was always ready to help and has proven to be a pleasant learning environment.

Phebe Van de Heyning

Table of Contents

Abstract

The objective of this thesis is to analyse the current state of the Aula Magna of the Faculty of Law of the Universitat de València. This room is used as a lecture hall and for chamber music performances. By measuring *in situ* the acoustic parameters of the hall the current situation can be analysed. The measurements are performed with an omnidirectional source and 22 receiving points. The measured acoustic parameters are compared to the recommended values, to analyse the current state of the hall.

A 3D model is made using AutoCAD2013, the model only consists of 3D-faces. This model is imported in a room acoustics software, Odeon 10.1Combined. After placing the source and receivers and assigning the materials, the model can be changed to match the reality. By changing the sound absorption coefficients of the materials, the model is adjusted to the measurements *in situ.* The model is a reliable presentation of the real hall if the results that are simulated by Odeon are the same as the measurements *in situ*.

In the 3D model alterations can be made to improve the hall for a lecture or a chamber music performance. Changes are tested with the recommended values for the acoustical parameters for both usages of the hall. Double-sided tiles with a reflective and absorbent side, together with two movable panels are the proposal to improve the acoustic conditions. When there is a lecture the two movable panels are stored behind the screen and the tiles show the absorbent side. For a chamber music performance the tiles are turned to the reflective side and the two panels are placed on stage. This proposal leads to a significant improvement for both usages of the hall. It is easy to employ and will make a big difference for the experience of the audience.

List of figures, graphs and tables

List of figures

List of graphs

List of tables

List of abbreviations and symbols

Abbreviations

AI	Articulation index
AL_{CONS}	Articulation loss of consonants
BR	Bass ratio
br	Brilliance ratio
CIS	Common intelligibility index
EDT	Early decay time
NC curve	Noise Criterion curve
NR curve	Noise Rating curve
RASTI	Rapid speech transmission index
RC curve	Room Criterion curve
RT	Reverberation time
SDI	Surface diffusivity index
SII	Speech intelligibility index
TR1	Timbre ratio
SPL	Sound pressure level in dB
SPL(A)	Sound pressure level in dB(A)
STI	Speech transmission index

Symbols

α	Sound absorption coefficient
C50	Clarity measured for sound arriving in the first 50 ms
C80	Clarity measured for sound arriving in the first 80 ms
D50	Definition for sound arriving in the first 50 ms
D80	Definition for sound arriving in the first 80 ms
dB	Decibel
LF80	Early lateral energy fraction for sound arriving in the first 80 ms
LG80*	Old name for $Lj(Average)_{80}^{\infty}$
$Lj(Average)_{80}^{\infty}$	Late lateral sound level for sound arriving after first 80 ms
Hz	Hertz
L_A	Sound pressure level
T10	Reverberation time measured over a decay of 10 dB
T15	Reverberation time measured over a decay of 15 dB
T20	Reverberation time measured over a decay of 20 dB
T30	Reverberation time measured over a decay of 30 dB
Ts	Centre time

1 Objective

In this thesis the acoustic parameters that are important for analysing a space are explained as well as an analysis of the current state of the Aula Magna of the Faculty of Law of the Universitat de València. The third part is about improving the hall.

Analysing the current situation of the hall is executed by testing the measurements *in situ* of the hall, using the recommended values for the acoustic parameters. The measurements are also used to adjust the 3D model in Odeon (room acoustics software), in order that the simulated results are similar to the *in situ* measurements. The 3D model is made with AutoCAD 2013, using only 3D faces. If the model is equal to the reality, improvements can be tested with the simulated results.

The space that is researched is the Aula Magna of the Faculty of Law of the Universitat de València. The hall is mainly used for lectures. A second usage of the hall is chamber music performances. These two usages require different acoustic properties. The objective of this thesis is to propose a feasible and easy system in order that the room can be used for a lecture and for chamber music performances.

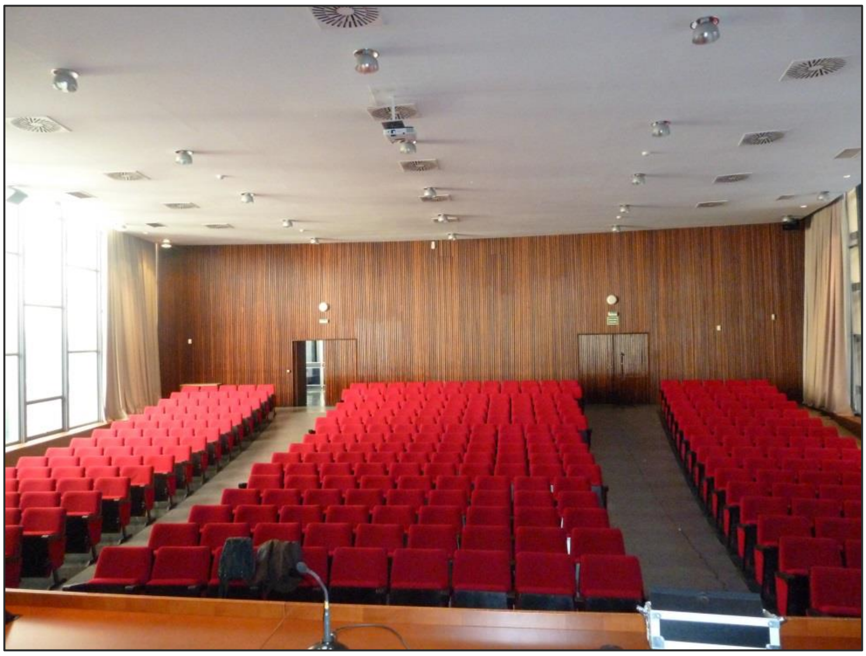


Figure 1.1 - Photo of the Aula Magna of the Faculty of Law of the Universitat de València

2 Sound quality parameters of an auditorium

This chapter gives a description of the most important quality parameters needed for analysing the acoustic measurements. These acoustic parameters are intended for determining the acoustic quality of spaces that are used for musical performances and the spoken word.

2.1 General design parameters

2.1.1 Hall size

In a concert hall a smaller room creates an intimate experience, but to make profit halls are often very big so there are more seats to sell. Beranek investigated in 1996 [1] a correlation between the experience of the listener and the size of the hall. He cited that the capacity of the best halls was about 1850 seats and 2800 seats.

2.1.2 Hall volume

The hall volume influences the reverberation time, a very important parameter in the acoustical analysis of a room. A high volume per seat ratio is needed to control extreme loudness at low capacities. At high capacities a low volume per seat ratio is necessary to create an intimate environment.

2.1.3 Hall shape

The most used shapes in concert halls are presented in figure 2.1. In Beranek's paper (1996) [1] the shape that appeared the most in his top list of halls was the shoebox floor plan. A rectangular plan offers strong lateral reflections necessary for a full experience.

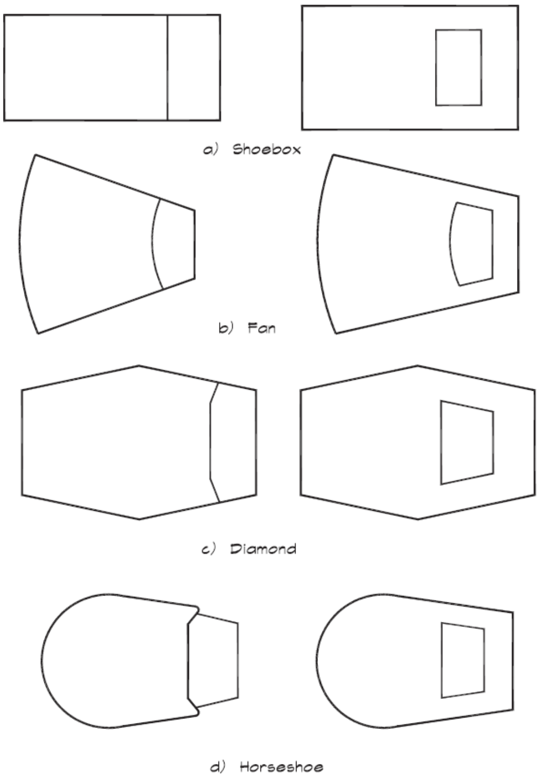


Figure 2.1 - Basic floorplans for concert halls in normal (left) and surround (right)

2.2 Level of ambient noise

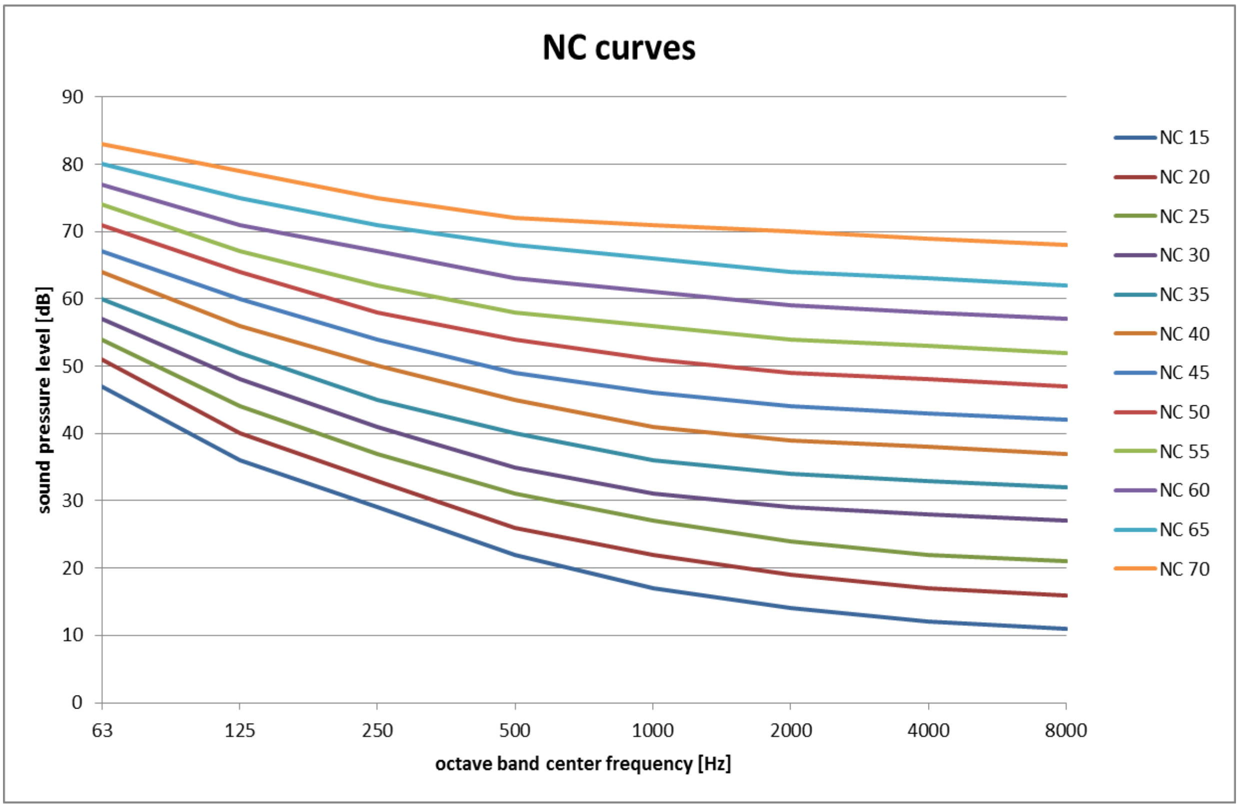
The level of ambient noise, also called background noise, is any noise other than the sound that is being examined. Different sources can be the cause of background noise: activities in adjoining spaces, traffic from the street, conditioning systems, lighting, etc. The ambient noise can hinder the normal activity of space.

To evaluate the interference, noise criterion curves (NC curves) can be used. NC curves were developed in the US in 1957 for evaluating indoor noise and satisfactory conditions for speech lucidity. A set of criteria curves going from 63 to 8000 Hz are used. The curves define the maximum sound pressure level (dB) per octave band so that activities in certain spaces are not obstructed. The NC rating can be achieved by plotting the octave band levels for a noise spectrum on a graph together with the NC curves. The NC rating is the lowest NC curve which is not surpassed by the spectrum. Since the interval between NC curves is 5 dB, interpolation is used between two curves.

The NC level depends on the measured spectrum, but can also be related to an overall A-weighted level or dBA level.

$$NC \cong 1{,}25(L_A - 13)\ [2] \tag{2.1}$$

With: NC = NC level [dB]
L_A = sound pressure level [dBA]



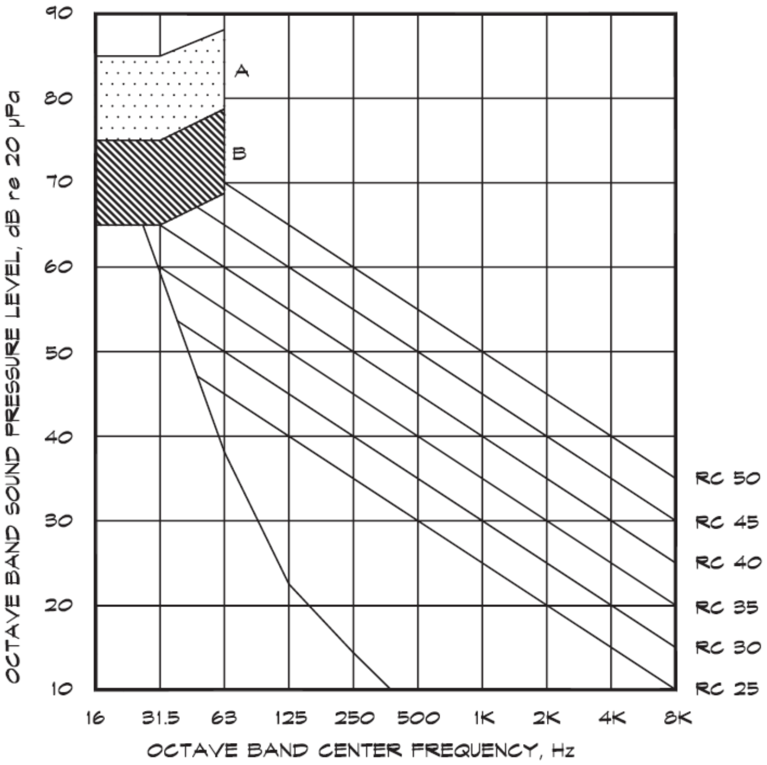
Graph 2.1 - NC curves

In 1981 Blazier [3] designed another set of curves, the room criterion (RC) curves. The values used in the RC curves originate from a study of HVAC noise in office spaces by ASHRAE (American Society of Heating, Refrigeration, and Air Conditioning Engineers). The curves are straight lines. In comparison with the NC curves, the RC curves are more strict for the lower frequencies but they give a 5 dB margin.

The final RC level is the arithmetic average of the 3 RC levels corresponding to the 500, 1000 and 2000 Hz octave band values, taken from the measured spectrum. For the frequencies equal and lower than 500 Hz a parallel line is drawn 5 dB above the 500 Hz value, this line is called the rumble limit. For the frequencies above 2000 Hz a parallel line 3 dB above the value for 2000 Hz is drawn, this curve is called the hissy limit. If the measured spectrum exceeds the rumble limit the RC level is given the designation R, if it exceeds the hissy limit it is given an H. Otherwise the designation is N for Normal. For example the RC value can be RC 29 (H).

The two regions (A and B) shown on the curve define the values where mechanical vibrations can be a nuisance in lightweight structures. In this report there are no lightweight structures.

In the ASHRAE Handbook, edition 1987, interior noise design goals are stated in a table [4]. Where ASHRAE has recommended that an acoustical engineer should be consulted, the values from a research study from the national research council (US, 1959) [5] is used. These values are marked in the table with an *.



Graph 2.2 - RC curves

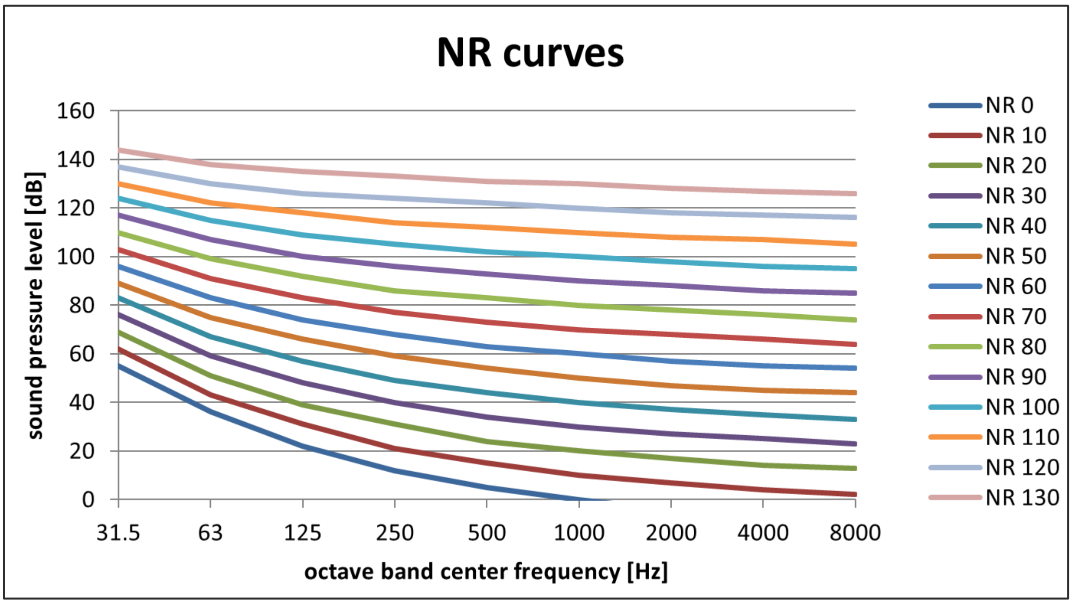
Table 2.1 - Recommended NC and RC [6]

Type of area	**recommended NC or RC criteria range**
1 Private Residences	25 to 30
2 Apartments	25 to 30
3 Hotels/motels	
a Individual rooms or suites	30 to 35
b Meeting/banquet rooms	25 to 30
c Halls, corridors, lobbies	35 to 40
d Service/support areas	40 to 45
4 Offices	
a Executive	25 to 30
b Conference room	25 to 30
c Private	30 to 35
d Open plan areas	35 to 40
e Computer equipment rooms	40 to 45
f Public circulation	40 to 45
5 Hospitals and clinics	
a Private rooms	25 to 30
b Wards	30 to 35
c Operating rooms	35 to 40
d Corridors	35 to 40
e Public areas	35 to 40
6 Churches	25 to 30

7 Schools		
	a Lecture and classrooms	**25 to 30**
	b Open plan classrooms	30 to 35
8 Libraries		35 to 40
9 Concert halls		15 to 20*
10 Music rooms		**25***
11 Legitimate theatres		20 to 30
12 Recording studios		15 to 20*
13 Movie theatres		30 to 35

As seen in the table the recommended NC value for a lecture room is NC 25 to NC 30. In the ASHRAE Handbook edition 2011 the level is set at NC 25 for a lecture and a classroom, in the research study from the National Research Council this is NC 25 as well. If music is played in the auditorium the recommended curve is the NC 25 curve. The limit for the RC criteria is RC 25. In this report the acoustic criteria must meet the NC 25 curve or the RC 25 curve if there is a lecture or a musical concert. In table 2.3 the values are shown for the NC 25 curve and the RC 25 curve. The total ambient noise may not exceed 35 dBA and all the measured values per octave band must be below the values shown in this table.

Besides NC curves and RC curves, there are another set of curves developed by Kosten and van Os (1962) [7] and the International Organization of Standardization (ISO/R 1996:1971) [8] to define the acceptable background level. These are called the noise rating curves or NR curves. The NR value is the highest value of an NR curve that is not exceeded by the measurements. The NR value can be presented per octave band. The total NR value is the highest of the individual NR values for the frequency bands. In table 2.2 the recommended NR curve is shown for different applications.



Graph 2.3 - NR curves

Table 2.2 - Recommended noise rating curves

Type of space	NR value	Sound pressure level [dBA]
Kindergartens	30	35
Auditorium	25	30
Library	30	35
Cinema	30	35
Concert hall	20	25
Music room	25	30
Court room	25	30
Theatre	25	30
Store, retail	35	40
Supermarkets	40	45
Church	25	30
Office	30	35
School, lecture room	25	30
Studio, radio	15	20

The recommended value for a lecture room and a music room for the NR criterion is NR 25. The maximum values are shown in table 2.3.

Table 2.3 - Summarized values for NC 25, RC 25 and NR 25

F [Hz]	31.5	63	125	250	500	1000	2000	4000	8000	*Global*
NC 25 [dB]	/	54	44	37	31	27	24	22	21	*35dBA*
RC 25 [dB]	50	45	40	35	30	25	20	15	10	
NR 25 [dB]	/	55	44	35	29	25	22	20	18	*30dBA*

NC curves and RC curves are mostly used in the United States, the NR curves on the other hand are more common in Europe.

2.3 Spaces dedicated to musical performances

In a musical performance, the music is obviously important. But the space where the performance takes place is as or even of more vital importance. From the instrument to the ear, the sound moves through the space: it is reflected, absorbed and dispersed. Therefore it is essential that the material and shape of the surfaces are well-designed. To rate the acoustic quality different parameters can be defined. These parameters are known as quality parameters. In the next paragraphs the quality parameters are explained.

2.3.1 Reverberation time and liveness

Liveness or reverberation is a parameter most used in concert halls. The reverberation time is the time required for the sound to decay 60 dB below the maximum. It represents the rate of the decay of the sound, not the total duration of the reverberation. It can also be measured over another range (T10, T15, T20, T30) and then multiplied to get the value for 60 dB. For example the time the sound needs to drop 10 dB multiplied with a factor 6 is T10. If the reverberation time is long, it will take longer for the sound to decay. These kinds of spaces are said to be 'live rooms', the room is reflective. If the room is absorbent, the sound will decay more rapidly, these rooms are called 'dead rooms'.

In the late 1890s Wallace Clement Sabine (published in 1900) [9] developed an equation for the reverberation time in a room. As seen in the formula the reverberation time is proportional to the volume of the space. Thus the size of the room is vital for a good reverberation time. It is an empirical formula and the accuracy of the reverberation time prediction is never perfect. This equation is the basis of most reverberation time predictions in auditoria.

$$RT60 = 0{,}1611 \frac{V}{\sum_{i=1}^{n} \alpha_i S_i} \tag{2.2}$$

With: RT60 = reverberation time [s]
V = volume of the space [m^3]
S = surface area [m^2]
α = absorption coefficient, between 0 and 1 (fully absorbent = 1) [-]

In 1930 Carl Eyring [10] published another equation based on an idea from R.F. Norris (1932) to calculate the reverberation time of a space. This equation is more precise for dead rooms (with absorptive materials). The result is called the Norris Eyring Reverberation Time.

$$RT60 = \frac{0.1611\, V}{-S_T \ln(1-\bar{\alpha})} \tag{2.3}$$

With: S_T = total surface area [m^2]
$\bar{\alpha}$ = average absorption coefficient, between 0 and 1 (fully absorbent = 1) [-]

$$\bar{\alpha} = \frac{S_1\alpha_1+S_2\alpha_2+S_3\alpha_3+ \ldots +S_n\alpha_n}{S_T} \tag{2.4}$$

S_i = surface area of surface i [m^2]
α_i = absorption coefficient of surface i [-]

The major absorbing surface in an auditorium is the audience. Sabine first calculated the reverberation time on the basis of the number of seats, but Beranek (1969) found that treating the audience like another material gave more accurate results. Beranek presents a table, showing the coefficients. Absorption by people is hardly dependent on the material of the chair. If the seat is unoccupied, then the material is important.

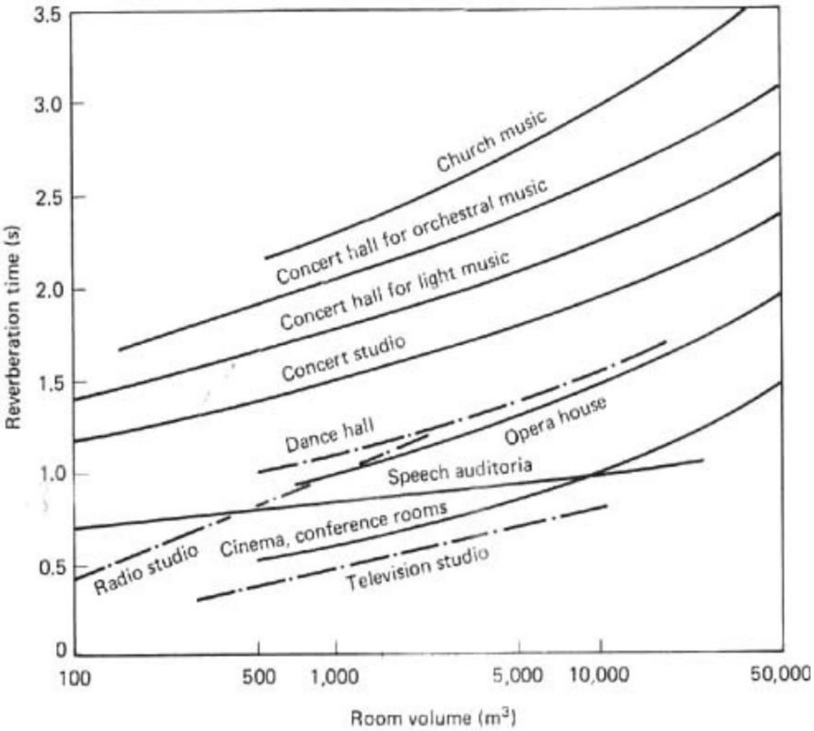
Table 2.4 - Absorption coefficients of surfaces in auditoria [11]

	Frequency [Hz]				
	125	250	500	1000	2000
Audience and orchestra	0.39	0.57	0.80	0.94	0.92
Upholstered seats, unoccupied	0.32	0.50	0.73	0.87	0.85
Leather-covered thinly, upholstered seats, unoccupied	0.12	0.20	0.28	0.34	0.34
Plaster or thick wood	0.19	0.14	0.09	0.06	0.06
Plaster on concrete block	0.12	0.09	0.07	0.05	0.05
Concrete	0.02	0.02	0.02	0.04	0.05
Thin wood panelling	0.42	0.21	0.10	0.08	0.06
Curtain (velour, draped)	0.06	0.31	0.44	0.80	0.75

Liveness is primarily related to the reverberation time of the mid and high frequencies, above 500 Hz. The reverberation time is not the same for high as for low frequencies. Therefore it is best to work with a curve showing the reverberation time per frequency. In this report the used frequencies are the centre of the octave band spectrum (63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz). When one number is needed it is called the average reverberation time. It is the average reverberation time of 500 Hz and 1000 Hz.

The reverberation time is a handy tool to quantify the acoustic quality of a room. Every musical performance room has an optimum reverberation time. This optimum depends on the purpose of the room, the total volume of the room and the type of music.

Beranek (1962) [12] writes about the recommended value for the reverberation time for the mid frequencies in relation to the volume of the hall. The volume of the Aula Magna of the Faculty of Law is 1650 m^3. In the next graph the recommended values for the Aula Magna of the Faculty of Law can be deduced.



Graph 2.4 - Recommended reverberation time as a function of room volume

In 1993 Barron [13] published the recommended occupied reverberation times, shown in table 2.5. These values are for large halls, the hall in this report is a small hall. Therefore the values in the table may be lower. For the bass tones a longer reverberation time is recommended to get a warm sound, an increase between 20% to 50% is needed.

Table 2.5 - Recommended occupied reverberation times [13]

Type of music	Reverberation time [s]
Organ	> 2,5
Romantic classical	1,8 – 2,2
Early classical	1,6 – 1,8
Opera	1,3 – 1,8
Chamber	1,4 – 1,7
Drama (spoken word)	0,7 – 1,0
Lecture	0,7 – 1,2

The recommended reverberation time for a lecture hall is around 0,7 to 1,2 seconds and between 1,4 and 1,7 seconds for chamber music for a big concert hall.

In the Sabine equation the reverberation time is proportional to the volume per seat (if the incidental absorption other than the audience is ignored). For a long reverberation time a big volume per seat is required. The ratio volume/seat is used in the first steps of the design. According to Barron 10 m^3/seat is the minimum for concert halls, for opera houses the ratio should be 7–9 m^3/seat and 4 m^3/seat for a drama theatre.

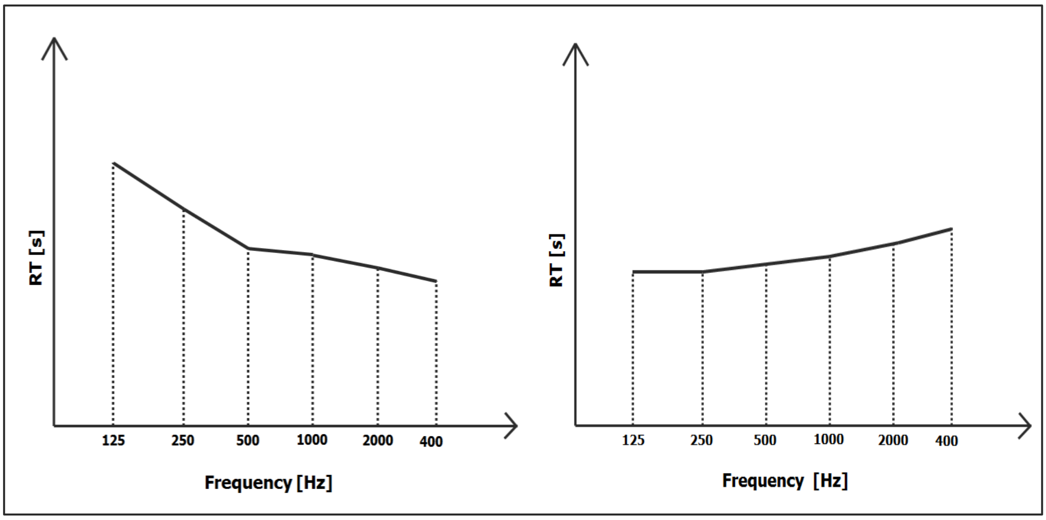
Table 2.6 - Volume/seat ratio in relation to the reverberation time

6-7 m^3/seat	RT < 1,5 s
7-9 m^3/seat	1,5 s < RT < 2 s
9-11 m^3/seat	RT > 2 s

The early decay time (EDT) is another measure for liveness. It is the reverberation time calculated from the first decrease of 10 dB multiplied by six, it is written as T_E. It is measured in an unoccupied room. Beranek cites in his study about concert halls (1996) [1] that the difference between T_E (unoccupied) and T_{60} (occupied) is 0,3 seconds.

$$T_E \cong T_{60} + 0.3 \;\; [\mathrm{s}] \tag{2.5}$$

For a hall where music is played the reverberation time of the bass frequencies must be higher than the reverberation times of the mid and high frequencies. For an unamplified speaker the reverberation times of the high frequencies should be longer than the reverberation times of the bass and mid frequencies. This is because the high frequencies have the shortest wavelength and will decay faster than the longer wavelengths. Therefore the high frequencies must reverberate longer in the space.



Graph 2.5 - Reverberation time curve for a music hall (left) and for a speech room (right)

2.3.2 Warmth

A sense of musical warmth is achieved if there is a bass reverberation. The reverberation time of low frequencies (below 350 Hz) must be higher than the mid frequency (500 Hz or 1000 Hz). But the difference cannot be too great, if the different frequencies are perceived unevenly, it gives a feeling that the room rumbles. The warmth of a sound in a certain space is quantified (Beranek, 1962) [12] by the ratio between the average low-frequency reverberation times and the average mid frequency reverberation times. The ratio is called the bass ratio.

The bass ratio is a value between 1 and 1,5. Beranek states that for a reverberation time of 2.2 seconds a BR of 1,1 – 1,25 is recommended, if the reverberation time is around 1,8 seconds the bass ratio should be around 1,1 – 1,45.

$$BR = \frac{T_{60}(125)+T_{60}(250)}{T_{60}(500)+T_{60}(1000)} \tag{2.6}$$

2.3.3 Brilliance

A room has brilliance if sounds are perceived as bright, clear, a ringing sound and rich in harmonics. A brilliance sound has slowly decaying high-frequency components. When there is too much brilliance the sound will seem harsh and metallic sounding. Basically it is the opposite of warmth. Brilliance is the ratio of the reverberation times of the high frequencies to the reverberation times of mid frequencies. It is recommended that br is higher than 0,85 for the majority of rooms.

$$br = \frac{T_{60}(2000)+T_{60}(4000)}{T_{60}(500)+T_{60}(1000)} \tag{2.7}$$

Another ratio that can be used for evaluating comparative aspects of brilliance is the Timbre Ratio, TR1 (Schmidt, 1979) [17]. If TR1 > 1 the reverberation times of the higher frequencies are longer than these of the lower frequencies. If this is the case a room will have higher brilliance than warmth in its sound perception.

$$TR1 = \frac{T_{60}(2000)+T_{60}(4000)}{T_{60}(125)+T_{60}(250)} \text{ [18]} \tag{2.8}$$

2.3.4 Intimacy

Intimacy is used to determine a space where there is a perception that music is being played in a small room. Beranek (1962) [12] relates intimacy to the initial delay time of the first reflection (t_I). The initial delay time is the difference in milliseconds between the arrival time of the strongest reflection, minus the arrival time of the direct sound, at the centre of the audience seating area [14]. If the initial delay time is less than 20 milliseconds, a space can be called intimate. If it is more than 35 milliseconds the quality of a musical performance will decrease substantially. Intimacy is not only dependent from the initial delay time, but it is a good indication. Intimacy is regarded as one of the most important parameters for musical acoustics.

2.3.5 Loudness (direct sound and reverberant sound)

A person standing in a room listening to music, hears sound waves coming from all directions. Some sound waves will be direct and other waves will have been reflected. How we experience loudness depends on the direct sound and on the reverberant sound.

There is a big difference between small and big spaces. In small rooms the direct sound will reach the last person with sufficient loudness. In big rooms this is not the case, when the direct sounds reaches the last people the loudness has decreased too much. The solution is not to make rooms too big and by covering the surfaces of the room with reflective materials shaped in a way that the rear seats will hear the sound as well as the front rows. To control the loudness of a room, calculating the volume per seat can be useful. The volume per seat must increase if the number of seats decrease. If there are few seats, a large volume is needed to control the loudness.

The reverberant sound energy depends on three variables: the intensity of the reflected sound perceived by the listener, the reverberation time between the listener and the orchestra and the volume of the room. For example if the room is rather small and the reverberation time is high, an orchestra can become overwhelming for the audience. In a study about concert halls Ando (1985) [15] cites that the overall average maximum sound levels are favoured in the 77 dBA to 80 dBA range.

2.3.6 Clarity or definition

Clarity concerns the quality of sound transfer to the listener, if the sound in a room can be heard clearly it is said that the room has definition. The opposite of clarity is fullness, this is when it is difficult to differentiate multiple sounds. The degree of definition is related to the reflective surfaces of the space and is thus associated to the intimacy of the room. Furthermore clarity is linked with the reverberation time and therefore clarity is also associated with the liveness of the room. The fact that you are close to the source or farther away is also important for the clarity, as well as the total volume of the room. Clarity can be connected to the loudness of the direct sound and the reverberant sound.

Clarity can be measured in the form of the parameter C50 or C80. C50 and C80 are values expressed in dB. C50 can be defined (Riechardt, 1975) [16] as the ratio of the sound energy arriving before the first 50 milliseconds since the arrival of the direct sound to the late arriving sound energy (after the first 50 msec). For the parameter C80 the ratio is the sound energy before the first 80 millisecond since the arrival to the sound energy arriving after the first 80 milliseconds.

A second parameter to measure clarity is D50 or D80. It is the ratio of the early arriving sound energy (before the first 50 or 80 milliseconds since the arrival of the direct sound) to the total sound energy ratio. D50 and D80 are expressed in percentage.

$$D_{50} = \frac{\int_0^{0.050\,s} p^2(t)dt}{\int_0^{\infty} p^2(t)dt} \tag{2.9}$$

$$\mathrm{D}_{80} = \frac{\int_0^{0.080\,\mathrm{s}} \mathrm{p}^2(\mathrm{t})\mathrm{dt}}{\int_0^{\infty} \mathrm{p}^2(\mathrm{t})\mathrm{dt}} \tag{2.10}$$

$$\mathrm{C}_{50} = 10\log\left(\frac{\mathrm{D}_{50}}{1-\mathrm{D}_{50}}\right) \tag{2.11}$$

$$\mathrm{C}_{80} = 10\log\left(\frac{\mathrm{D}_{80}}{1-\mathrm{D}_{80}}\right) \tag{2.12}$$

With: p = the sound pressure as a function of time

C50, C80, D50 and D80 are measured when the room is unoccupied. A higher value for these parameters, because of strong early reflections, shows greater clarity. This parameter is more important for rooms such as auditoria where the spoken word is the main source for sound. D50 values are preferred to be higher than 0.5% for the entire spectrum of frequencies.

Another indicator for clarity is the centre time or Ts parameter, expressed in milliseconds. It is the time of the centre of gravity of the squared impulse response. A high value for Ts means poor clarity.

$$Ts = \frac{\int_0^\infty t\,.\,p^2(t)dt}{\int_0^\infty p^2(t)dt} \tag{2.13}$$

2.3.7 Envelopment and lateral energy fraction (LF80)

Early reflections coming from lateral directions create a sense of spaciousness, this was discovered by Marshall (1967) and published in the scientific journal: Journal of Sound and Vibration [19]. He named this phenomenon ‘spatial responsiveness’ and later ‘spatial impression’. Now it is referred to as envelopment. Envelopment is the perception for the audience that sound is arriving from all directions. Studies by Marshall (1967) and Veneklasen and Hyde (1969) [20] prove that for a fulfilling experience envelopment is very important. It is furthermore very important that the sound reaches the left ear at the same time it reaches the right ear. Together with Barron, Marshall developed the early lateral energy fraction (LF80). LF80 is defined as the linear ratio of the lateral early energy to the total early energy [21]. ‘Early’ indicates the sound energy before the first 80 milliseconds since the arrival of the direct sound. Direct sound itself is excluded from the formula. How higher the LF80 value, the greater the degree of spatial sound. This parameter is important for musical performances.

$$LF80 = \frac{\int_{0.005}^{0.080} \mathrm{p_L}^2(\mathrm{t})\mathrm{dt}}{\int_0^{0.080} \mathrm{p}^2(\mathrm{t})\mathrm{dt}} \tag{2.14}$$

With: p_L = lateral energy as a function of time
p = total energy as a function of time

The lateral energy fraction can be calculated per octave band, the lateral energy fraction of a total room is the average of the LF80-values corresponding to the octave frequency bands of 125 Hz, 250 Hz, 500 Hz and 1000 Hz. The lateral energy fraction is being referred to as LF_{E4}. The value for LF_{E4} is recommended to be higher than 0,15.

The parameter $Lj(Average)_{80}^{\infty}$ is suggested by Bradly and Soulodre (1995) [22] as another measure for spatial impression.

$$\mathrm{Lj(average)}_{80}^{\infty} = 10\log\left(\frac{1}{4}\int_{\mathrm{N125Hz}}^{\mathrm{N1000Hz}} \int_{0.080}^{\infty} \mathrm{p_L}^2(\mathrm{t})\mathrm{dt}\right) \tag{2.15}$$

With: p_L = lateral energy as a function of time

2.3.8 Diffusion

Diffusion is the scattering of noise in various directions, so that the reverberated sound reaches the public at different times. It is the consequence of irregular surfaces, such as statues, balconies, etc. If all the surfaces are smooth there would be no diffusion. There is a noticeable difference for a listener if the depth of the unevenness is equal or greater than a ¼ of a wavelength. The diffusion of a room can be quantified with the surface diffusivity index (SDI), defined by Haan and Fricke (1997) [23].

Table 2.7 - Numerical values for SDI [24]

- High diffusivity (SDI = 1)
    - coffered ceiling with deep (>100 mm) recesses
    - random diffusing elements over the whole surface (>50 mm deep)

- Medium diffusivity (SDI = 0,5)
    - broken surfaces with shallow recesses (<50 mm deep)
    - flat surface behind a semi-transparent hard screen

- Low diffusivity (SDI = 0)
    - smooth flat or curved surfaces
    - absorptive surface

The SDI for the complete auditorium is the weighted average according to the surface area. In the literature it is generally accepted that diffusion is good for the colour of the sound. But there is no consensus on how much diffusion is wanted and how to exactly measure it. Quantifying diffusion is rather difficult because it is dependent on the frequency, the angle of the sound wave and the material of the surfaces.

2.3.9 Balance and blend

Balance means an equal intensity among the different elements of the orchestra and the vocal participants. Blend is a symphonic combination of the orchestral sounds. A good balance can be achieved by a well-designed concert hall in terms of width, depth, seating plan and the surfaces. For example the roof should have reflective panels and the surfaces should have some irregularities. The blend of an orchestra depends profoundly on the shape of the roof above the artists and on surfaces that can mix the sound before reaching the audience. Both balance and blend are important to a musical performance and thus the design of a concert hall.

2.3.10 Immediacy

Immediacy is the perception that a room rapidly responds to a note. This is influenced by the early reflections returned to the musicians. If it takes too long for a sound to reflect to the ear of the artist, he will hear it as an echo. Immediacy is determined by the intimacy, liveness, diffusion and echo. An echo is a long delayed reflection with enough intensity, returned to the listener.

2.3.11 Dynamic range

The dynamic range is the variety of sound levels received in the room. It goes from the lowest background level, mostly coming from the murmuring of the audience, to the highest level, coming from the orchestra/musical performance. The highest level should not be uncomfortable for the audience. Ando (1985) [15] cites that the overall average maximum sound levels for concert halls are favoured in the 77 dBA to 80 dBA range.

2.3.12 Ensemble

The audience needs to hear the members of the orchestra playing in unison. Some concert halls have places in the seating plan where the sound quality is poor. Because of balconies or irregularities even echoes can occur in some places in the hall. The clarity or the feel that there is ensemble can vary according to where you are in the hall.

2.4 Spaces dedicated to lectures

Understanding a speech or listening to music is very different. Listening to a lecture can be more objectively and easily measured. Quantifying and enjoying music is rather subjective, everyone has different preferences, but for the spoken word this is not the case. Understanding what someone is saying is an objective question, it depends on the acoustic properties of the room as well as the linguistic capabilities of the speaker.

The goal of a lecture is that everyone in the room understands the speaker. Therefore the main criterion is speech intelligibility. Understanding words entails that the speech is loud enough to be heard over the background noise, so that every syllable can be heard. A balance needs to be found between reverberation time and absorption. With an increase in reverberation time, clarity decreases but the intensity drops if there is excessive absorption.

Another important aspect for a good speech intelligibility is the preservation of the high frequencies. The materials used for the surfaces in the room must not absorb a lot of high frequencies. There must be a balance between all octave bands. In an auditorium the volume needs to be minimized, excessive sound levels can overload the absorbent material resulting in a higher reverberation time. If the reverberation time is too long, sounds will overlap and words will sound blurred.

2.4.1 Speech intelligibility

Speech intelligibility is the parameter to discuss the understanding of speech and the spoken word. When someone hears two or more tones at the same time with different sound levels the quieter one will be the most difficult to understand. It is believed that the quieter sound is masked by the louder one. The intelligibility can be measured using different parameters.

2.4.1.1 Articulation index (AI)

The articulation index (AI) was the first method developed by French and Steinberg (1947) [25]. A group of people is presented to a series of phonemes. In the test logatoms are used, these are structured (consonant-vowel-consonant) nonsense pseudo-words, so that the context cannot be used to understand these words. An example of logatoms are 'DAK' and 'FRUP'. The fraction of syllables understood is the AI, the result is a value between 0 and 1. The AI is 1 if all the syllables are understood. Beranek states in a scientific article [26] that if the AI is less than 0.3 the experience will be unsatisfactory. Between 0.3 and 0.5 the values are acceptable, between 0.5 and 0.7 good and the intelligibility is considered excellent if the AI is above 0.7.

2.4.1.2 Speech intelligibility index (SII)

The speech intelligibility index or SII is a parameter between 0 and 1. It measures the clarity of spoken messages by taking the ratio of understood sounds to the total aired sounds. A high value for the SII is achieved if the direct sound component is strong as well as the first reflections (after 10 to 30 milliseconds). If this is the case there is few energy left for reverberation. The speech intelligibility index has formally replaced the articulation index as the official parameter. It is defined by ANSI, the American National Standards Institute, in 1997 [27]. In this report the formulas and methods can be found.

2.4.1.3 Articulation loss of consonants (AL_{CONS})

The articulation loss of consonants is a percentage to quantify speech intelligibility. It is the fraction of consonants wrongly understood. The articulation loss of consonants can be put in a formula (Preutz, 1971) [28], where AL_{CONS} is related to the reverberation time (RT [s]), room volume and distance.

$$r_l = 0.21\sqrt{\frac{V}{T_{60}}} \tag{2.16}$$

$$AL_{CONS} = \frac{200.r^2.RT^2}{V} \qquad \text{if } r < r_l \tag{2.17}$$

$$AL_{CONS} = 9.RT \qquad \text{if } r > r_l \tag{2.18}$$

With: r_l = limiting distance [m]
r = talker to listener distance [m]
V = room volume [m^3]

2.4.1.4 Speech transmission index (STI)

The speech transmission index is a ratio for speech transmission quality, it was developed by Steeneken and Houtgast [29] (officially published in 1980). STI measures the ability of the room to transport the sound wave from the speaker to the listener. It can be used for an unamplified speaker as well as an amplified sound. The scale goes from 0 to 1. Later another scale was introduced, the common intelligibility scale (CIS) (Barnett and Knight, 1995) [30]. This scale is related to the STI value and goes from 0 to 1. In an auditorium an STI value higher than 0.45 or a CIS value higher than 0.65 is recommended.

$$\mathrm{CIS} = 1 + \log(\mathrm{STI}) \tag{2.19}$$

The STI value can be computed for a female and a male voice, these values can be different because a man's voice has typically a lower frequency than a woman's voice. These parameters are called STI male and STI female. STI was at first a parameter used only by a small group of researchers. When Brüel and Kjaer (1985) [31] introduced RASTI the method became more widespread. RASTI or Rapid STI is an approximation of the full STI. This method is significantly faster than measuring the full STI. A full STI measurement is performed at 7 octave bands and for 14 modulation frequencies, thus a total of 98 separate values, a RASTI measurement only uses 9 of the possible 98.

Table 2.8 - STI value, CIS value and corresponding quality of speech transmission

STI value	CIS value	Quality
0 – 0.3	0 – 0.48	bad
0.3 – 0.45	0.48 – 0.65	poor
0.45 – 0.6	0.65 – 0.78	fair
0.6 – 0.75	0.78 – 0.88	good
0.75 – 1	0.88 – 1	excellent

2.5 Echoes, focusing and resonances

Echoes, focusing and resonances should be minimalized in every room. To stop echoes from occurring, the surfaces should be made of absorbent materials. If the delay between the initial sound and a second sound is more than 65 milliseconds, an annoying echo is perceived. At delay times below 50 msec a not-annoying echo is detected. Where the delay time is less than 30 msec the two sounds will feel as merged, and no echo is observed even if the second sound is 5dB more than the initial sound (Blauert, 1983) [32].

When a surface is concave sound waves can focus on a single place. This is called focusing: it is the accumulation of sound energy in particular areas of a room, this causes sound concentrations.

Acoustic resonance is the possibility of an element to increase a frequency that equals one of its own natural frequencies of vibration. To stop this effect it can be useful to know the resonance frequencies of different elements. Another precaution is not to use parallel panels near the sound source.

3 Project description and acoustic objectives

3.1 Properties of the hall

The subject of this acoustic study is the Aula Magna of the Faculty of Law of the Universitat de València (UV). The auditorium has a fan floor plan, the space widens to the rear. The floor has an inclination to improve visibility. The front wall and the back wall of the room have a curvature. The auditorium has one axis of symmetry. The materials that are used for the surfaces and other elements in the room are cited in table 3.2.

Table 3.1- Main properties of the auditorium

Volume	1650 m^3
Number of seats	307
Surface area of the perforated roof	68,79 m^2
Maximum height	4,80 m
Width	19,55 m
Length	23,45 m
Surface area of the stage	71,68 m^2

Table 3.2 - List of the different materials used for the auditorium with numbering

Element	Description	Number
Side, front and back of the room	Plywood panelling, stiffened externally by decorative vertical battens.	1
Doors	Plywood, 5 cm thick.	2
Scaffold	3cm wood on wooden studs with an average thickness of 12cm.	3
Absorbent ceiling area near the podium	Plasterboard, 15mm, with circular perforations of 11%, these perforations are filled with 10mm Rockwool with air plenum of 10cm.	4
Flat roof	Double plasterboard plate 13 + 13mm on 36mm grid with rock wool in its spaces suspended by silent-blocks. Plenum with average thickness of 12cm.	5
Seats	Seats lined with fabric	6
Floor	Linoleum glued to the original floor	7
Glass wall	Large panes of glass, 8mm thick, in a metal frame. This glass has lightweight curtains to control outside light.	8

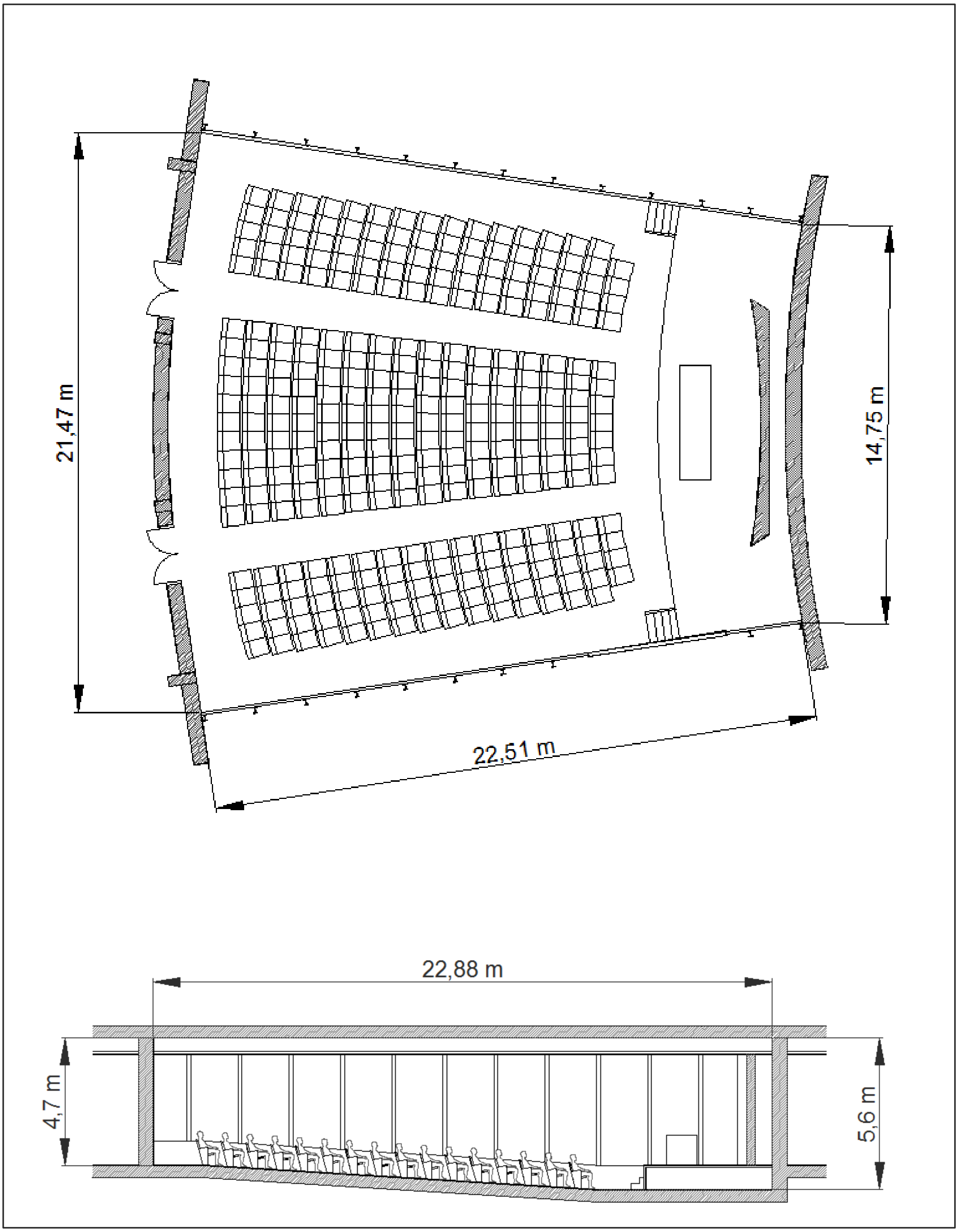


Figure 3.1 - Floor plan and section plan

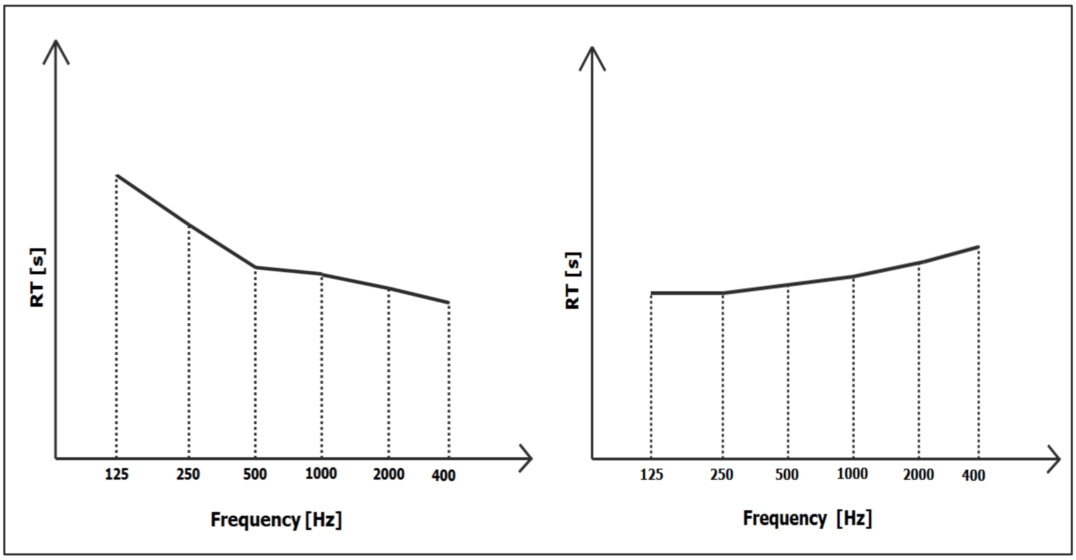
3.2 Acoustic objectives

The Aula Magna of the Faculty of Law at the Universitat de València is used as an auditorium for lectures and for playing chamber music. Chamber music is a type of classical music that is composed for a small group of instruments. In accordance with the main goal of the room the recommended values of the parameters listed in chapter two are presented in the following table. Intimacy, warmth and brilliance are not important for a lecture, speech intelligibility on the other hand is not valuable for enjoying chamber music.

Table 3.3 - Recommended values for the acoustic parameters

Main purpose of the room	**Lecture auditorium, speech**	**Chamber music**
Volume [m^3]	1650	1650
Level of ambient noise	NC-25, RC-25, NR-25	NC-25, RC-25, NR-25
Intimacy t_I [s]	≤ 35 msec	≤ 20 msec
Reverberation time [s]	0,7 – 1,2	1,0 – 1,5
Warmth		1,1 – 1,45
Brilliance		>0,85
Speech intelligibility, STI	>0,5[1]	
Clarity, Definition	D50 > 0,5 %	D50 > 0,5 %

The curves of the reverberation times for the two different uses of the hall should be similar to the graphs shown below.



Graph 3.1 - Reverberation time curve for a music hall (left) and for a speech room (right)

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[1] Spanish standards ask for a minimum of 0,5 instead of 0,45

4 Analysis of the current state

4.1 Method

To analyse the current state of the hall measurements need to be made in the auditorium. These measurements *in situ* will be used to adjust the 3D model. The measurements itself are also analysed. In this chapter each step of the analysis of the current state of the auditorium is explained.

A 3D model of the Aula Magna of the Faculty of Law will be imported in a room acoustics software. Each surface is assigned with its corresponding material. After running the model the results are compared with the results that were measured in the hall. By adjusting the properties of the materials, the results should be similar to the results measured in reality. If the difference between the simulated results and the result from the *in situ* measurements are smaller than 10%, the 3D model is regarded equal to the reality.

4.2 Measuring the auditorium

In the hall a source is placed, by moving the receiver, measuring points are created. On the measuring points (as seen in figure 4.2) different parameters are measured per third of an octave band. The octave bands are 63 Hz, 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz. The parameters are EDT [s], T10 [s], T20 [s], T30 [s], T15 [s], RT [s], C50 [dB], C80 [dB], D50 [-], D80 [-], STI female [-], STI male [-] and RASTI [-].

The green dot shows where the source was placed throughout all the measurements, the red dots show where the signal was received. The source is set at the height where the mouth of a speaker should be, around 1m70. The source is not placed in the middle, to avoid symmetry. The measuring points make a grid around the audience.

The sound is transmitted by an omnidirectional sound source (Brüel & Kjaer, OmniPower 4292-L). The sound is received by the omnidirectional microphone of a sound level meter (Brüel & Kjaer, Sound Level Meter Type 2250). An amplifier is used (Brüel & Kjaer, Power amplifier Type 2734). The source and receiver are both connected to a computer with an USB Audio Interface (Brüel & Kjaer, USB Audio Interface ZE 0948). By doing this the computer can immediately link the transmitted noise to the received signal. The computer program used is DIRAC 5 (developed by Acoustics Engineering). A computer program is faster and has more possibilities than the processor of the sound level meter. Therefore DIRAC 5 is used and not the processor. The cable from the microphone to the computer should be as short as possible to minimize losses.

The transmitted sound is an exponential sweep (e-sweep), also called log-sweep. The frequency increases exponentially over time. The length of the sweep must be longer than the reverberation time of the room. Firstly a very long time for the sweep can be set to have an initial idea of the reverberation time, next the length can be adjusted to do all the measures of the space. In each position the e-sweep is played three times. All the results are saved as an audio file and the parameters are copied in an Excel file.

Figure 4.1 - Omnidirectional source

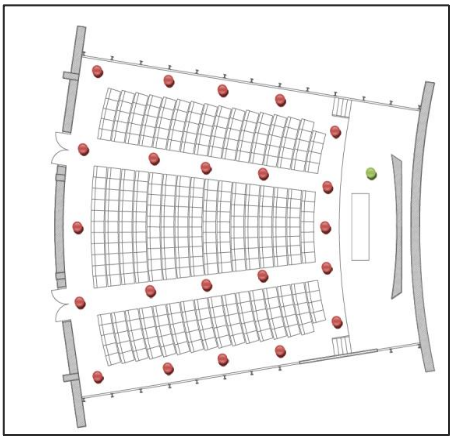

Figure 4.2 - Placement of the source (green) and receivers (red)

4.3 3D model and room acoustics software

4.3.1 Method

A 3D model in AutoCAD 2013 is designed using the floorplan, a section plan and photos of the hall. The model only consist of 3D-faces, there are no lines. With the software Rhinoceros 5 the file in .dwg is transformed to a .3ds file. This .3ds file is imported in a room acoustics software. This software is Odeon 10.1Combined[2]. Measuring points and the source are added to the model, using the same numbering and location as the measurements performed in the hall (Annex 1). Every surface is assigned with the correct material. Each material has got sound absorption coefficients for the different octave bands. By changing the sound absorption coefficient and comparing the real results with the results generated by Odeon the model can be adjusted. If the difference between the results given by Odeon and reality for T30 is less than 10% the 3D model is regarded as equal to the real one.

In Odeon results can be simulated for each measuring point. The parameters that are generated are EDT [s], T30 [s], SPL [dB], C80 [dB], D50 [-], Ts [ms], LF80 [-], SPL(A) [-], LG80* [-][3] and STI [-]. Results can also be obtained for the audience. Odeon can simulate the same parameters as for the single measuring points, for the audience. This is achieved by selecting the 3D faces where the audience should be and defining the dimensions of the grid. The smaller the dimensions of the grid the more precise the graphs.

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[2] Odeon A/S, Denmark, 1985-2009. Last revision date: 03/12/2009

[3] LG80* is the old name for $\mathrm{Lj(Average)}_{80}^{\infty}$

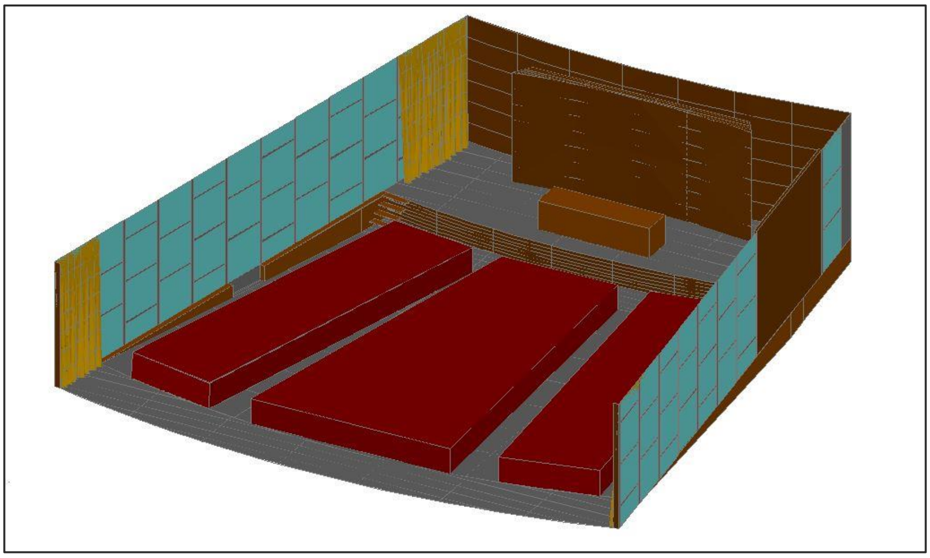

Figure 4.3 - 3D model in AutoCAD 2013

4.3.2 Laboratory measurement of the sound absorption coefficient

If a sound wave reflects on a surface, this surface can absorb a fraction of the energy. This fraction is quantified in the sound absorption coefficient. This number ranges from 0 to 1, with 0 being a perfect reflector with no absorption.

The reverberation room method is mostly used to measure the sound absorption coefficient of a material. This method is defined by the American Society for Testing and Materials (ASTM C423) [33] and International Organization for Standardization (ISO 354) [34]. In Europe the method from ISO is used.

The method is based on two reverberation times. The first is the value of the reverberation time in the reverberation chamber without the test material (formula 4.1) and the second value is with the test material placed on the floor (formula 4.2). A reverberation chamber has very hard surfaces, resulting in a long reverberation time. The reverberation time is calculated with the Sabine equation (Sabine, 1900) [9].

$$T_{60}(1) = \frac{0.161V}{S_T.\bar{\alpha}} \tag{4.1}$$

$$T_{60}(2) = \frac{0.161V}{S_T.\bar{\alpha} - S_1\alpha_0 + S_1\alpha_1} \tag{4.2}$$

$$\alpha_1 = \alpha_0 + \frac{0.161V}{S_1}\left(\frac{1}{T_{60}(2)} - \frac{1}{T_{60}(1)}\right) \tag{4.3}$$

With: T_{60} = reverberation time [s]

V = room volume [m^3]

$\bar{\alpha}$ = average absorption coefficient [-] see formula 4.4

S_T = total surface area [m^2]

S_1 = surface area of the test material [m^2]

α_0 = absorption coefficient of the surface covered by the test material [-]

α_1 = absorption coefficient of the test material [-]

$$\overline{\alpha} = \frac{S_1\alpha_1+S_2\alpha_2+S_3\alpha_3+ \dots +S_n\alpha_n}{S_T} \tag{4.4}$$

With: S_i = surface area of surface i [m^2]
α_i = absorption coefficient of surface i [-]

The position of the test material in the room can be important for the results. Samples placed in the centre of a surface have higher sound absorption coefficients than samples placed in the corners of the chamber. The average particle velocity is higher in the corners, explaining these differences. Annex B of the ISO 354:2003 [34] rapport gives a list of different mounting types.

All the materials of the auditorium can be placed in the reverberant chamber. The results can be used in the rooms acoustics software. Yet these values can be different from the values in the hall itself. This is because the material is mounted perfectly in the reverberant chamber and the placing method can be different in the hall. An extra air space can cause very different values than calculated with the Sabine equation. Therefore the sound absorption coefficients may be adjusted with a maximum of approximately 0,05 to match the 3D model to reality.

4.3.3 Adjusting the model

After importing the 3D model into Odeon and adding the source and receivers, the materials can be assigned. The absorption coefficients calculated with the Sabine equation of the materials are presented in the table below. The numbers correspond to the numbering of materials listed in table 3.2.

Table 4.1 - Sound absorption coefficients calculated with the Sabine equation for the used materials

	63 Hz	125 Hz	250 Hz	500 Hz	1K Hz	2K Hz	4K Hz	8K Hz
1	0.25	0.21	0.14	0.06	0.06	0.06	0.06	0.06
2	0.20	0.20	0.12	0.06	0.05	0.05	0.05	0.05
3	0.15	0.18	0.11	0.06	0.05	0.04	0.04	0.04
4	0.15	0.18	0.40	0.35	0.30	0.23	0.20	0.20
5	0.15	0.18	0.11	0.05	0.04	0.04	0.04	0.04
6	0.30	0.35	0.45	0.52	0.60	0.60	0.65	0.70
7	0.04	0.04	0.05	0.04	0.04	0.04	0.04	0.04
8	0.20	0.19	0.15	0.08	0.03	0.02	0.02	0.02

After assigning these properties to the corresponding surfaces, a first calculation can be made[4]. Most calculated values for 125 Hz, 2000 Hz and 4000 Hz fall within the 10% range. The values for 250 Hz are too low and too high for 500 Hz and 1000 Hz. By adjusting the properties of the sound absorption coefficients almost all values have a maximum difference of 10%. Once most of the points are similar to the results of the real measurements a more precise analysis is executed[5].

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[4] Engineering mode, impulse response length = 1500 ms.

[5] Precision mode, impulse response length = 1500 ms.

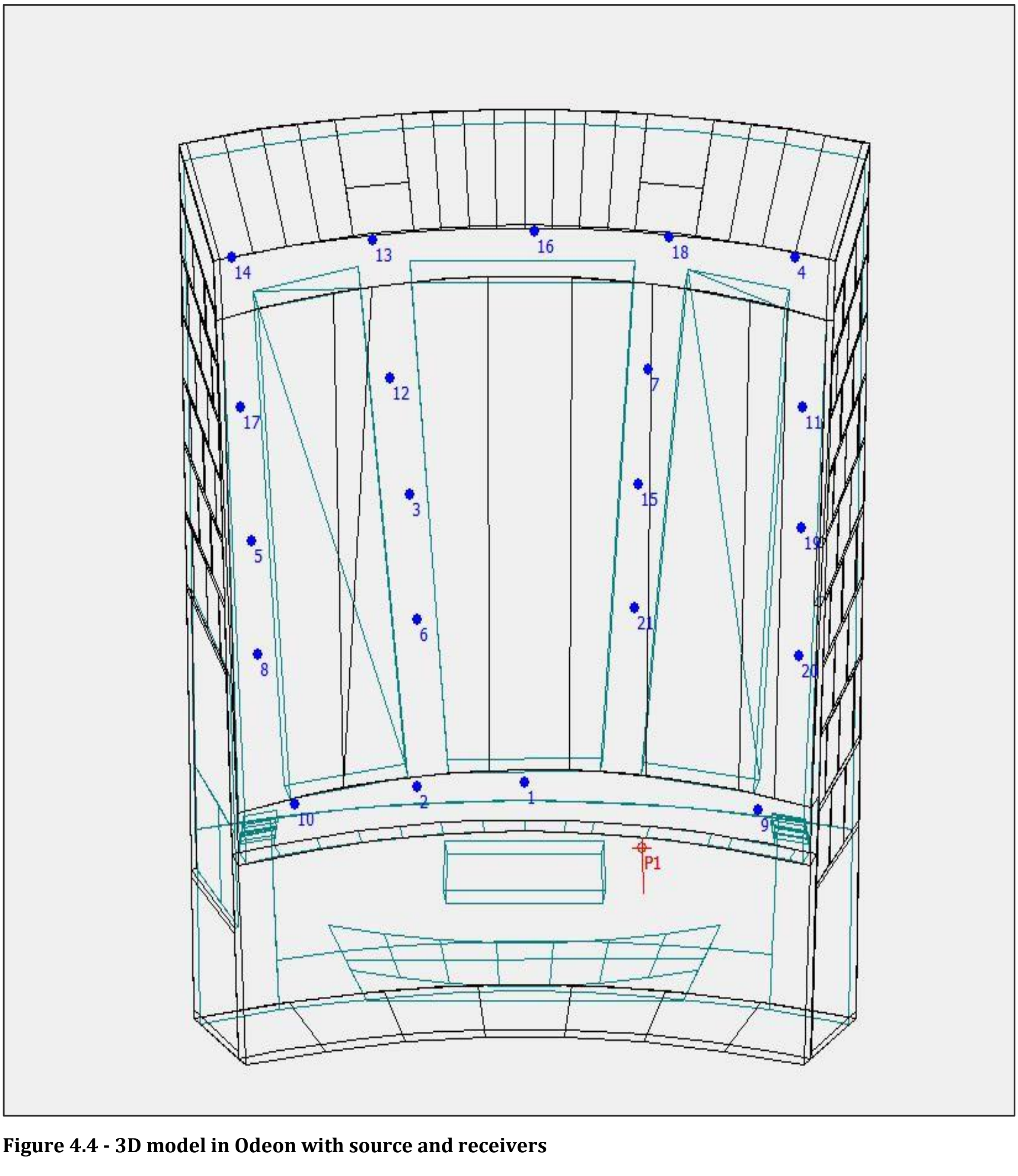


Figure 4.4 - 3D model in Odeon with source and receivers

The next table shows the values calculated in Odeon in precision mode. The values in green are values that have a difference smaller than 10%, the orange values a difference smaller than 15%. The values in red have a difference more than 15 %.

Table 4.2 - T30 [s] simulated with Odeon, after adjusting the materials

Position	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	0.88	0.78	1.15	1.23	1.03	0.93
2	0.86	0.76	1.14	1.24	1.04	0.91
3	0.83	0.8	1.15	1.23	0.99	0.91
4	0.85	0.81	1.16	1.2	1.04	0.91
5	0.87	0.79	1.22	1.27	1.06	0.95
6	0.85	0.8	1.16	1.19	1.04	0.91
7	0.87	0.77	1.19	1.2	1	0.88
8	0.87	0.78	1.17	1.24	1.07	0.94
9	0.88	0.8	1.19	1.23	1.03	0.92
10	0.87	0.83	1.2	1.27	1.04	0.93
11	0.9	0.81	1.18	1.19	1.04	0.95
12	0.83	0.79	1.15	1.21	1.03	0.93
13	0.9	0.76	1.12	1.24	0.97	0.93
14	0.87	0.76	1.2	1.23	1.04	0.9
15	0.85	0.78	1.18	1.21	0.99	0.91
16	0.86	0.79	1.15	1.19	1.02	0.92
17	0.87	0.82	1.18	1.2	1.06	0.91
18	0.86	0.81	1.17	1.23	1.02	0.92
19	0.89	0.76	1.17	1.2	1.01	0.9
20	0.87	0.76	1.18	1.18	1.02	0.89
21	0.83	0.77	1.15	1.22	1.01	0.91

Table 4.3 - T30 [s] results from the measurements performed in the hall

Position	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
1	0.974	0.702	1.08	1.24	1.022	0.923
2	0.873	0.808	1.16	1.275	1.013	0.945
3	0.912	0.747	1.216	1.298	1.013	0.97
4	0.827	0.767	1.137	1.321	1.051	0.999
5	0.947	0.738	1.267	1.282	1.08	0.95
6	0.831	0.761	1.216	1.289	1.064	1.019
7	0.995	0.725	1.159	1.256	1.037	0.939
8	0.941	0.769	1.174	1.231	1.04	0.937
9	0.932	0.708	1.182	1.161	1.025	0.928
10	0.785	0.408	1.155	1.204	0.992	0.905
11	0.909	0.806	1.237	1.297	1.021	0.949
12	0.929	0.801	1.204	1.254	1.055	0.93
13	0.947	0.812	1.148	1.221	1.042	0.941
14	0.825	0.742	1.212	1.249	0.929	0.956
15	0.875	0.812	1.189	1.406	1.114	0.969
16	0.854	0.779	1.251	1.405	1.13	1.016
17	0.878	0.821	1.171	1.4	1.067	0.893
18	0.896	0.734	1.223	1.349	1.084	0.997
19	0.858	0.758	1.196	1.344	1.057	0.957
20	0.566	0.716	1.218	1.242	1.044	0.99
21	0.76	0.748	1.147	1.31	1.026	0.933

To explain why there are two values simulated by Odeon that have a difference of more than 15% with the measurements *in situ*, the results simulated with Odeon (table 4.2) must be compared to the measurements *in situ* (table 4.3). The reverberation times (measured *in situ*) for point 10 for 250 Hz and for point 20 for 125 Hz are abnormally low and are not similar to the surrounding measuring points. Therefore a fault can be found in the results from the measurements *in situ* and not in Odeon or the material properties.

The adjusted sound absorption coefficients are presented in the table below. The maximum change is with 0,08 for two materials for 1000 Hz. The other materials already had a sound absorption coefficient of 0,02 for 1000 Hz and these values cannot be lowered. In realistic conditions a perfect reflector does not exist, a material will always absorb a fraction of the sound energy. Therefore the minimum sound absorption coefficient is 0,02. For the other materials the maximum change is with 0,06.

Table 4.4 - Sound absorption coefficients after adjusting the model

	63 Hz	**125 Hz**	**250 Hz**	**500 Hz**	**1K Hz**	**2K Hz**	**4K Hz**	**8K Hz**
1	0,25	0.25	0.19	0.02	0.02	0,06	0,06	0.02
2	0,20	0,20	0,12	0,06	0.02	0,05	0,05	0.02
3	0,15	0,19	0.16	0,06	0.02	0,04	0.02	0.02
4	0,15	0.21	0,46	0,35	0.22	0,23	0.17	0.14
5	0,15	0.20	0.17	0.02	0.02	0.04	0,04	0.02
6	0,30	0.39	0.51	0,51	0.52	0,59	0.60	0.62
7	0,04	0,04	0,10	0,04	0.02	0,04	0,04	0.02
8	0,20	0,19	0,21	0,08	0.02	0,02	0,02	0,02

With these material properties the model behaves the same as in reality and is therefore reliable and representative of the room.

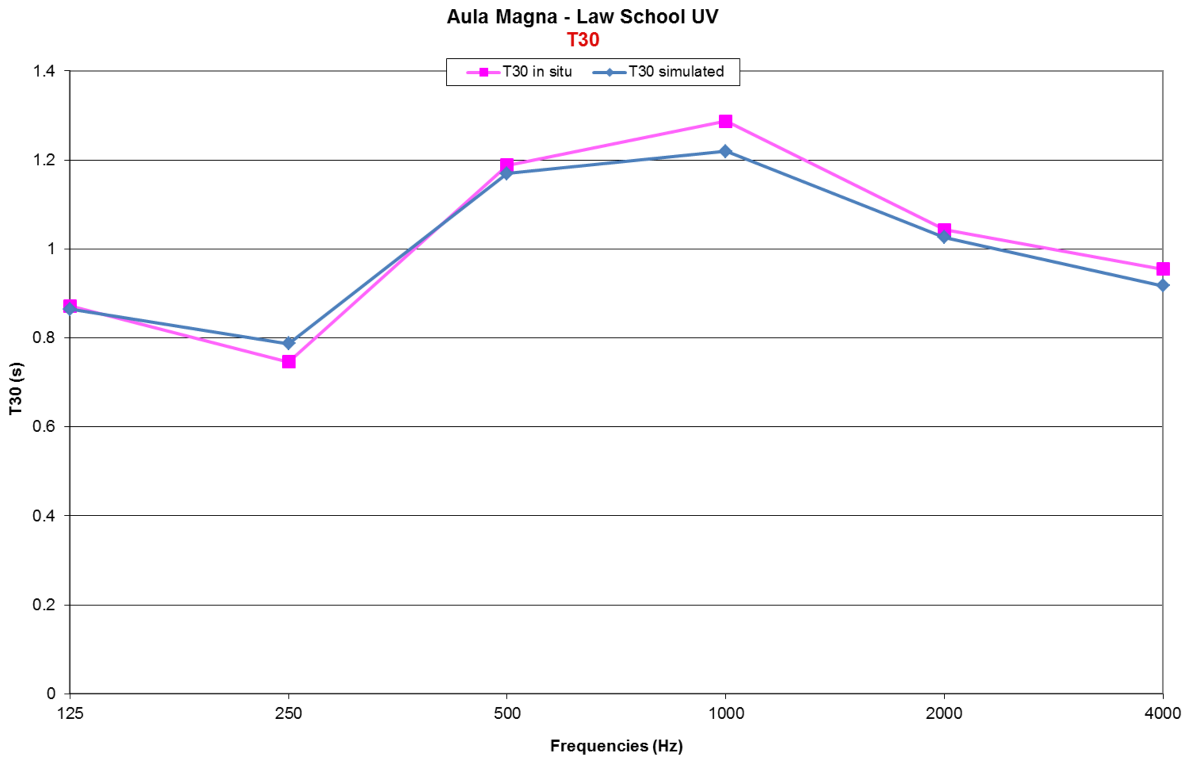
4.3.3.1 Comparison between in situ measurements and the simulation

The graphs in this section show the measurements *in situ* (in pink) compared to the simulated parameters by Odeon (in blue).

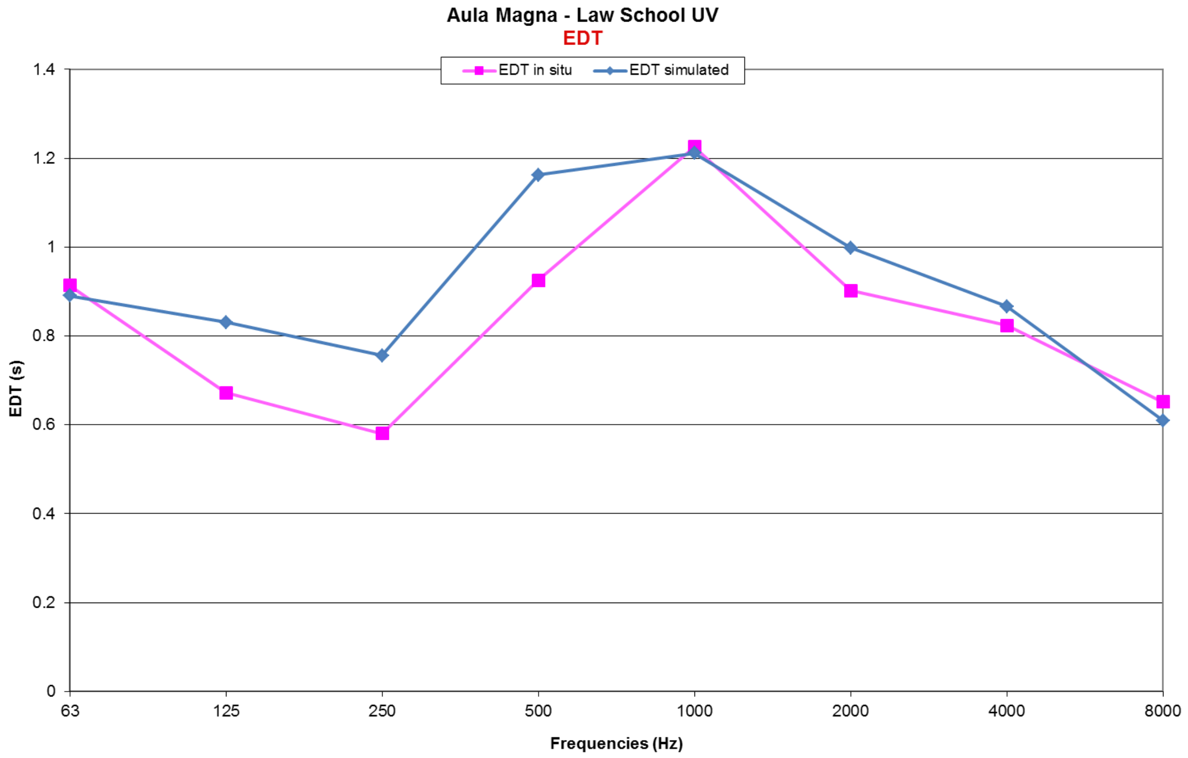
As seen on the graphics, the curves for T30 are almost similar. For EDT, C80 and D50 the general shape is the same, but there are some differences, especially for the bass frequencies.

Table 4.5 - Comparison STI *in situ* and simulated

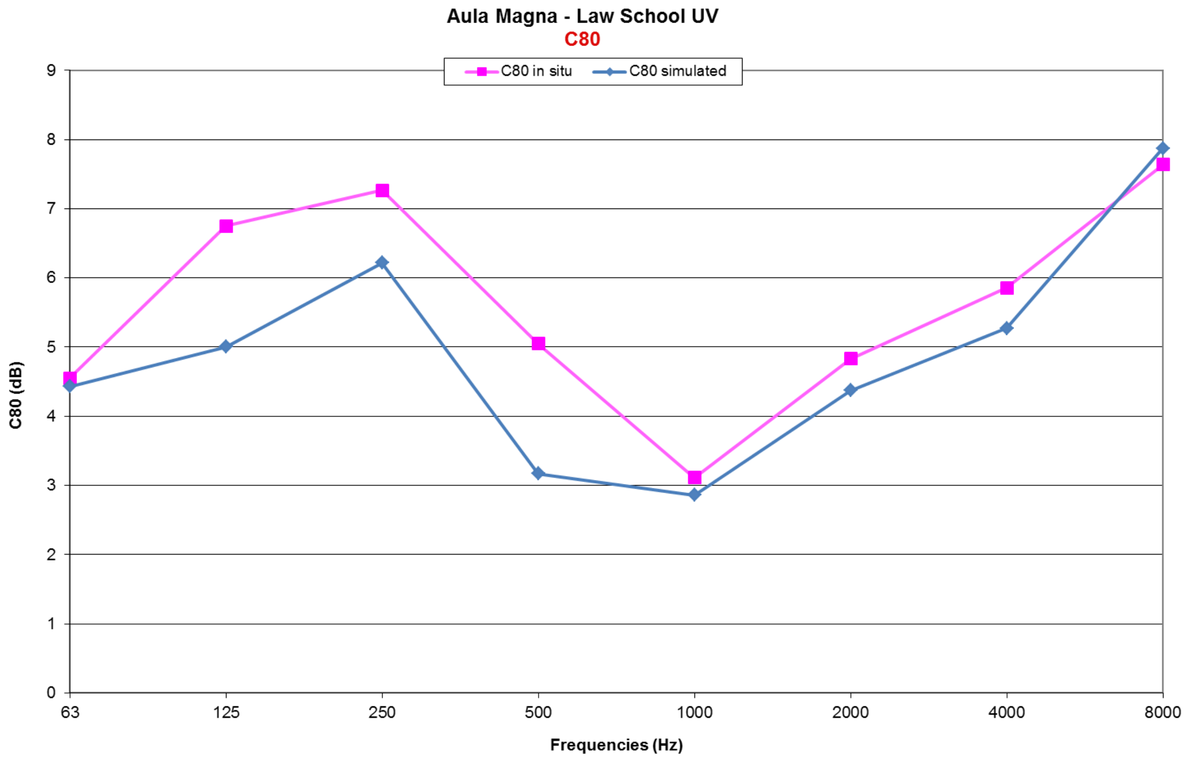
	average	**quality (table 2.8)**
STI *in situ*	0.64	Good
STI simulated	0.64	Good



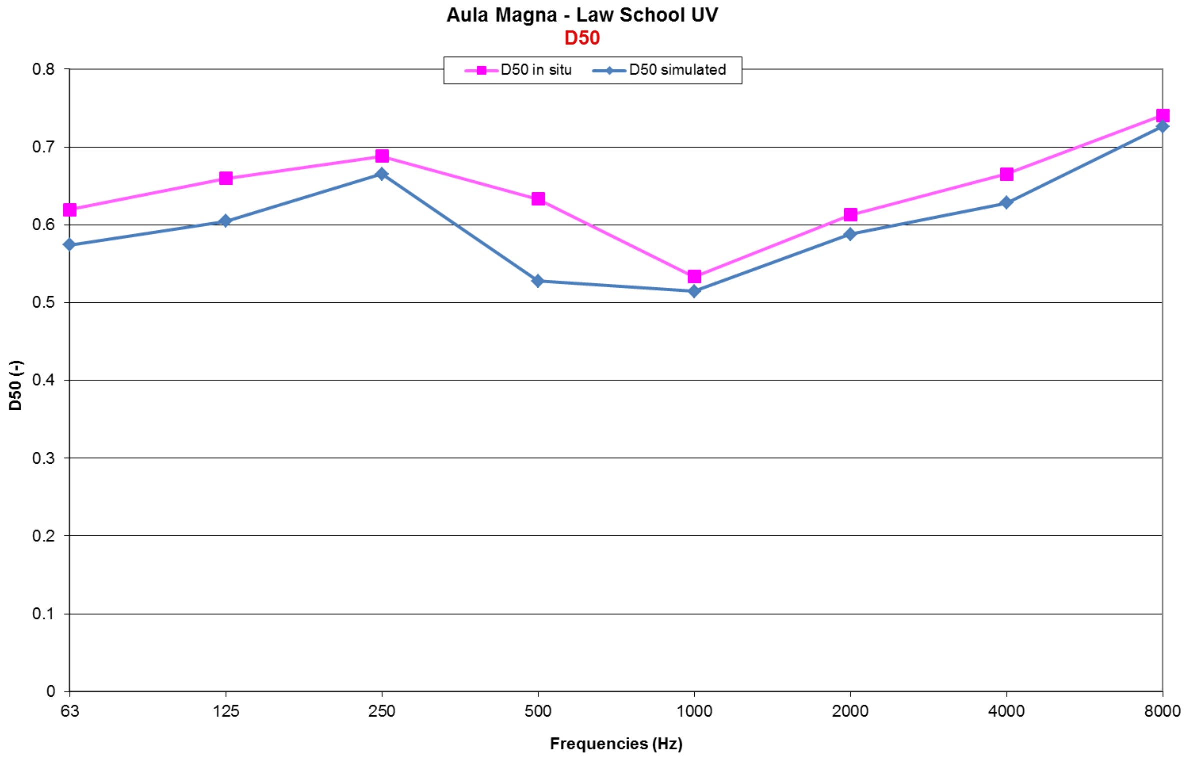
Graph 4.1 - Comparison between T30 *in situ* and simulated



Graph 4.2 - Comparison between EDT *in situ* and simulated



Graph 4.3 - Comparison between C80 *in situ* and simulated



Graph 4.4 - Comparison between D50 *in situ* and simulated

4.4 Conclusions about the current state

The visibility and first reflections are analysed using the floor plan and a section plan. The acoustic parameters are compared to the recommended values. The results are obtained from the measurements performed in the hall.

4.4.1 Visibility

To have a basic idea about the visibility quality, a simple model is constructed. A professor is talking behind his desk for a full auditorium. The mouth of the professor is at a height of 1,5 m. The eye height of a sitting student is 1,15 m. The inclination of the floor is 4°. As seen in figure 4.5 and figure 4.6 the last six rows cannot see the professor properly. In this auditorium the seats are placed right behind each other, if they are placed so that one can look between two people of the row in front, the visibility would improve greatly.

Because of the shape of the auditorium (widening towards the back), there are no obstacles to block the view on the professor. The only factor that reduces visibility is someone sitting in front.

The visibility is related to the speech transmission index of a place. If a person cannot see the professor, he will understand the lecture less than if he would see the professor.

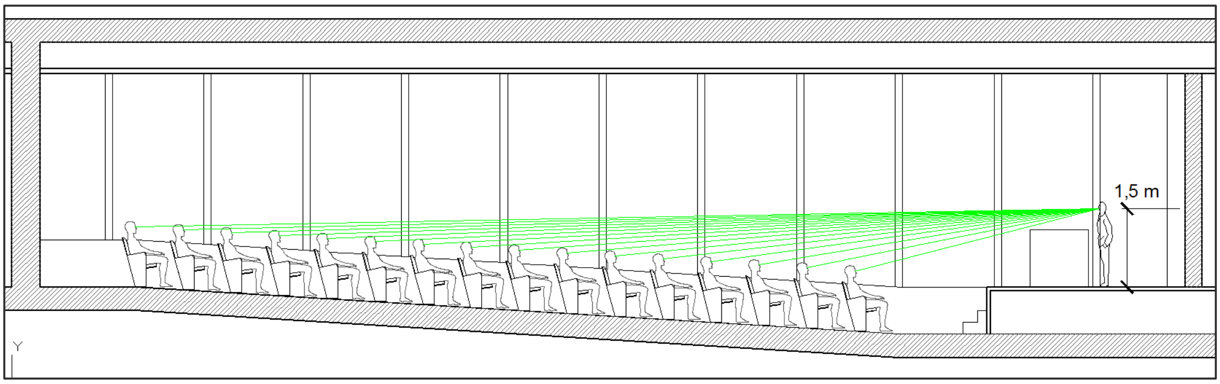


Figure 4.5 - Line of sight for all the students

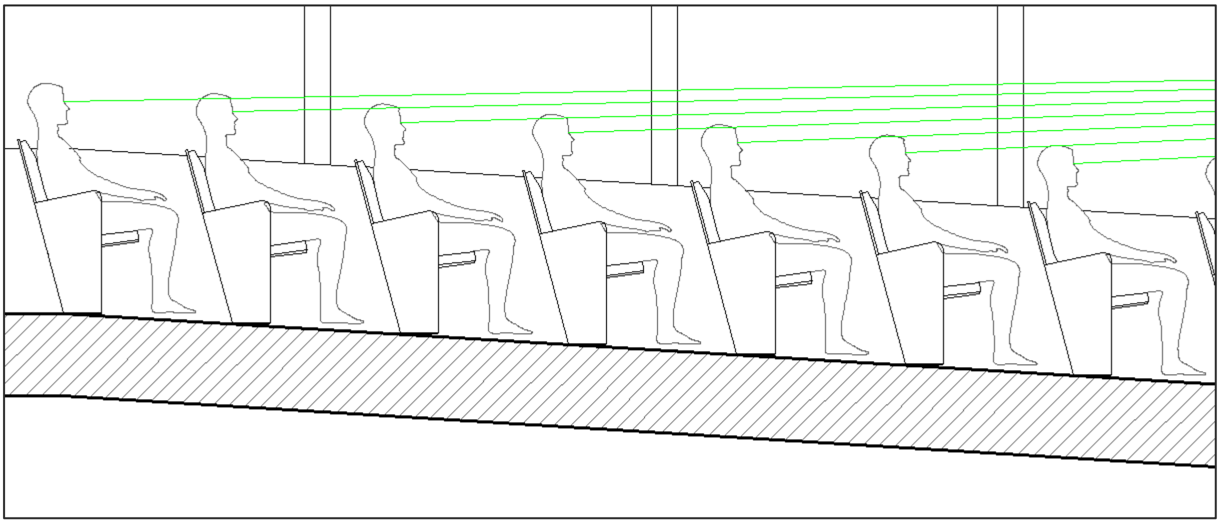


Figure 4.6 - Line of sight for the last 6 rows

4.4.2 First reflections of the sound

The direct sound waves and the trajectories of the first reflections are presented in the figures below. This is done for the first and the last row. In the figure it is indicated where the sound wave will reflect to reach the first and last row. The zone between these two points is the most important zone of the ceiling and walls in terms of acoustic improvement. The areas marked in red are the surfaces where all the sound waves will reflect to reach the audience (first reflection). If an improvement is needed in the ceiling or walls, these are the zones that need to be improved.

In the plan view, the professor is standing in one corner of the stage, resulting in a small area of the wall near him. If he would be standing in the other corner this zone would be significantly bigger. When designing the walls, it must be taken into account that the professor can move around.

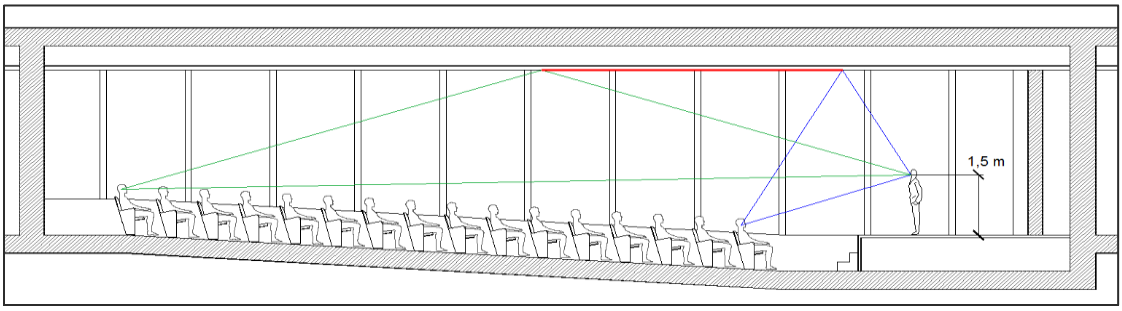


Figure 4.7 - First reflections of sound (in section)

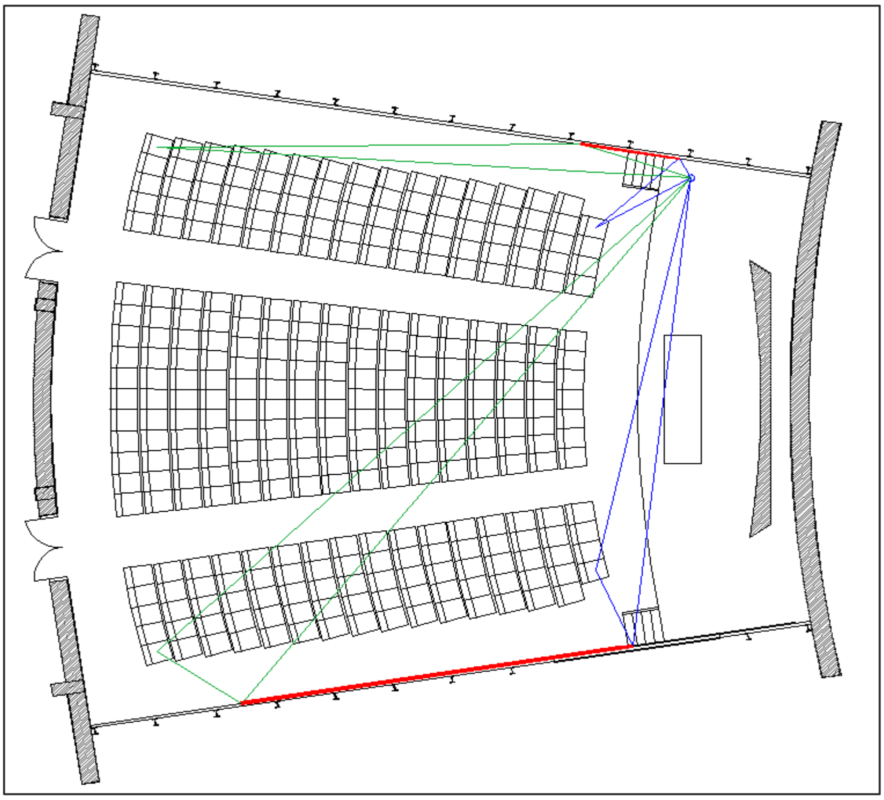


Figure 4.8 - First reflections of sound (in plan)

4.4.3 Analysis of the acoustic parameters

4.4.3.1 Analysing the measurements

Measure point 22 shows results that are not in line with the other results from the other measuring points, this is because the point is too close to the source. For the analysis of the auditorium, this point will be left out. The results of all the measurements *in situ* are listed in Annex 2 as well as the mean values.

C50 and C80

The values for C50 and C80 vary a lot for the different measuring points, showing differences between the measuring points near the stage and the measuring points at the back. The closer to the source, the higher the values.

D50 and D80

All the values are similar, except a very low value for D50 and D80 in measuring point 21 for 63 Hz. Point 21 is very close to the source, this could have caused this abnormality.

T10, T15, T20 and T30

The values for the low frequencies (63 Hz - 250 Hz) differ, above 250 Hz all the measuring points show similar values for T10, T15 and T20. Point 12 shows higher values for 63 Hz – 250 Hz in comparison to the other points.

There is no distinct difference between the measuring points for T30 except a very low value for measuring point 10 at 250 Hz. This point is near the stage, wall and the stairs.

Reverberation time (RT)

There is no distinct difference between the measuring points except a very low value for measuring point 10 at 250 Hz and a high value for point 12 at 125 Hz.

4.4.3.2 Comparison to the recommended values

The measured values can be compared with the recommended values listed in table 3.3.

Warmth

Warmth is measured with the bass ratio, as seen in the theoretical chapter (formula 2.6).

$$\mathrm{BR} = \frac{\mathrm{T}_{60}(125) + \mathrm{T}_{60}(250)}{\mathrm{T}_{60}(500) + \mathrm{T}_{60}(1000)} = \frac{0.895\ \mathrm{s}\ +\ 0.741\ \mathrm{s}}{1.112\ \mathrm{s}\ +1.297\ \mathrm{s}} = 0{,}678$$

It is recommended that this value is between 1,1 and 1,45 for playing chamber music. This is not the case. To improve this factor the reverberation time for the lower frequencies must be higher than the reverberation times of the mid frequencies. This problem will be addressed in the proposal for improvements. For a lecture this is not an important factor, but for a good music experience it can be crucial.

Brilliance

The brilliance ratio is used to quantify the brilliance, as seen in the theoretical chapter (formula 2.7).

$$\mathrm{br} = \frac{\mathrm{T}_{60}(2000) + \mathrm{T}_{60}(4000)}{\mathrm{T}_{60}(500) + \mathrm{T}_{60}(1000)} = \frac{1.046\ \mathrm{s}\ +\ 0.954\ \mathrm{s}}{1.113\ \mathrm{s}\ +1.297\ \mathrm{s}} = 0{,}829$$

The brilliance ratio should be higher than 0,85 when there is chamber music played. In the current state of the hall this is not the case. This condition could be met if the reverberation times of the mid frequencies would be longer or the reverberation times of the high frequencies shorter.

Definition

Not all the values for the D50 are higher than 0,50 %, the recommended value. Meaning that the clarity and definition in some points is not good enough for a lecture.

Table 4.6 - D50 values

F [Hz]	63	125	250	500	1000	2000	4000	8000
D50 min	0.28	0.44	0.50	0.50	0.39	0.49	0.56	0.62
D50 average	0.62	0.66	0.69	0.63	0.53	0.61	0.67	0.74
D50 max	0.88	0.85	0.83	0.76	0.72	0.76	0.84	0.90

Speech intelligibility

The speech intelligibility is in every point higher than 0,5, the recommended value.

Background noise

The criteria for the hall for both possible uses is the NC 25 curve. The background noise may not exceed the NC 25 curve. This means that the sum of the noise coming from the ventilation, lightning, other facilities and sound coming from the adjourning rooms must be limited. Sound insulation can decrease the noise coming from neighbouring spaces.

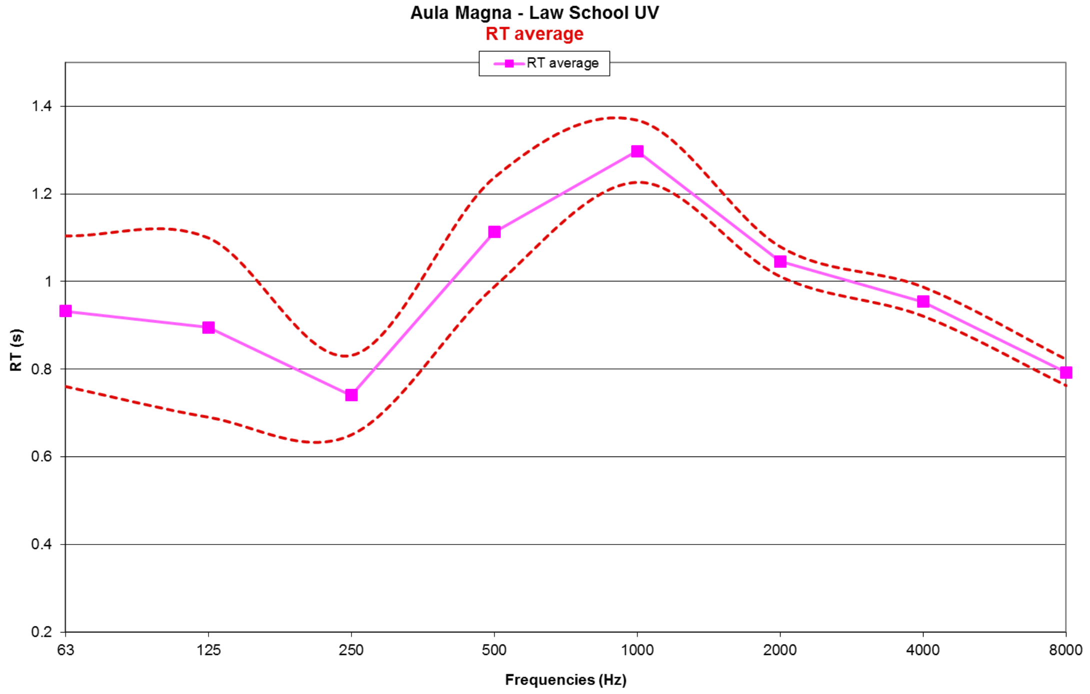
In the Aula Magna there is no problem with the background noise, therefore no improvements are needed.

Table 4.7 - NC-25 curve values

F [Hz]	63	125	250	500	1000	2000	4000	8000	*Global*
NC 25 [dB]	54	44	37	31	27	24	22	21	*35dB(A)*

Reverberation time

The average reverberation time for the mid frequencies is around 1,2 s. This is slightly too high for a lecture auditorium but good for a chamber music concert. The reverberation time curve does not have the recommended shape. This will be addressed in the proposal for improvements.



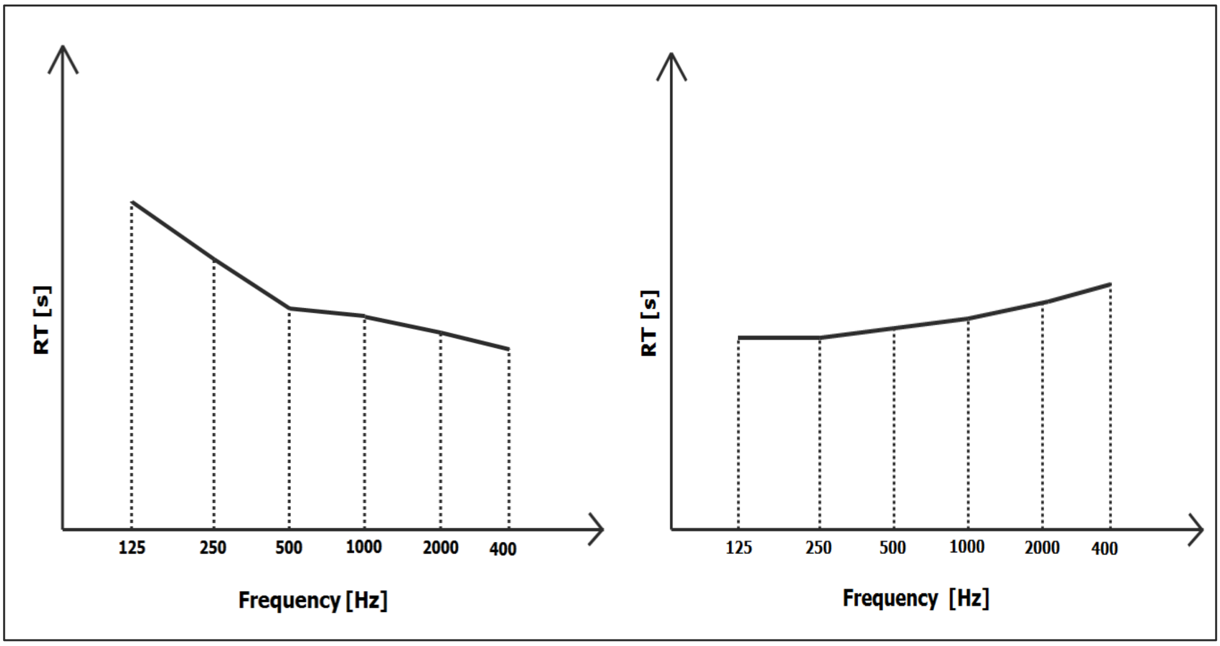
Graph 4.5 - Reverberation time of the Aula Magna

5 Proposal for improvements

5.1 Objectives

The Aula Magna of the Faculty of Law is used as a lecture room and as a music theatre for chamber music. The hall needs to have the correct properties for both usages. The main use of the hall is lectures. To achieve this the ceiling will be equipped with double-sided tiles and two movable panels on the stage. The tiles will have an absorbent side and a reflective side. The transportable panels have to be placed when there is a chamber music concert and the tiles will have to be turned over to the reflective side, in order to raise the reverberation time. These panels advance the properties of the hall as a music theatre.

The reverberation time is the most important parameter to modify. The reverberation time curve of the hall needs to be altered so that the bass ratio and brilliance ratio are better. The recommended reverberation curve for a lecture hall and a chamber music hall are different. The curves below show the perfect reverberation time curve for a music hall and for a lecture room. As discussed in the theoretical part of this project, the recommended reverberation time of the mid frequencies is 0,7 – 1,2 s for a lecture room and 1,0 – 1,5 s for a chamber music performance room.



Graph 5.1 - Reverberation time curve for a music hall (left) and for a speech room (right)

The objective is to design the double-sided ceiling tiles and the two movable panels so that during a lecture and a concert all the recommended values are met. The curves shown in graph 5.1 will be the starting point to design the acoustic panels and the double-sided ceiling tiles.

5.2 Noise reduction coefficient (NRC)

Acoustic panels or tiles are often quantified with their noise reduction coefficient (NRC). The NRC of a material is the average noise absorption coefficient from 250 Hz to 2000 Hz. This number gives a general idea about the characteristics of the material. For specific and precise calculations, the absorption coefficient for every frequency is needed.

$$\mathrm{NRC} = \frac{1}{4}(\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}) \tag{5.1}$$

Acoustic panels can be made from different materials depending on the purpose of the panel.

Wooden perforated acoustic panels are the most economical to change the properties of a space. By changing the hole diameters, hole spacing and thickness of the panel, different effects can be achieved.

5.3 Improving the properties of the hall for a lecture

5.3.1 Proposal for improvement for a lecture

To improve the experience during a lecture, acoustic ceiling tiles can be hanged on the ceiling, on the part where the sound waves first reflect. A panel on the walls is not an option because both walls are made out off windows.

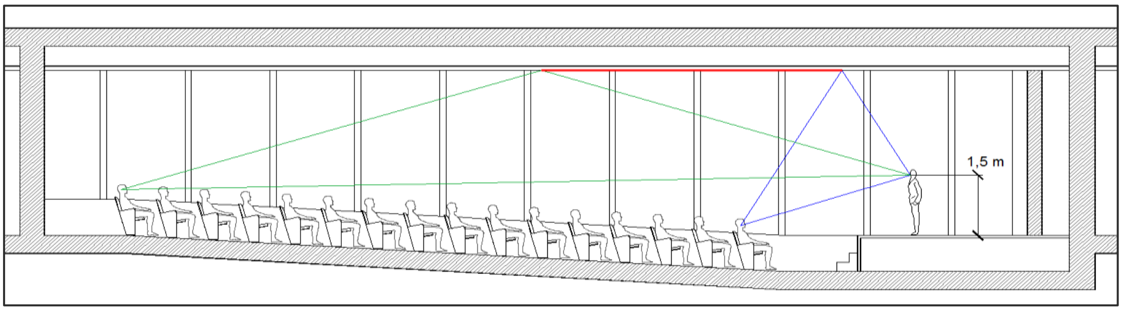


Figure 5.1 - First reflections of sound (in section)

One side of the ceiling tiles is used for a lecture. This side should absorb the sound energy of the mid frequencies in order to adjust the sound curve and lower the reverberation time. The recommended reverberation time for the mid frequencies for a lecture hall is 0,7 s – 1,2 s. Different materials can be used.

In this acoustic study mineral wool together with a perforated wooden panel is used as an absorber to improve the conditions of the hall during a lecture. But other materials with the same properties can also be used.

5.3.2 Properties of the acoustic tile – side 1

The tile is made of 40 mm mineral wool (60 kg/m3) combined with a perforated layer. This layer is made of 16 mm medium-density fibreboard (MDF Normal). MDF is an engineered wood product made by applying a high temperature and pressure to a combination of wood fibres, wax and a resin binder. The dimensions are presented in the figure below. This tile is designed by a Swiss company named Topakustik [34] (ceiling tile Type T).

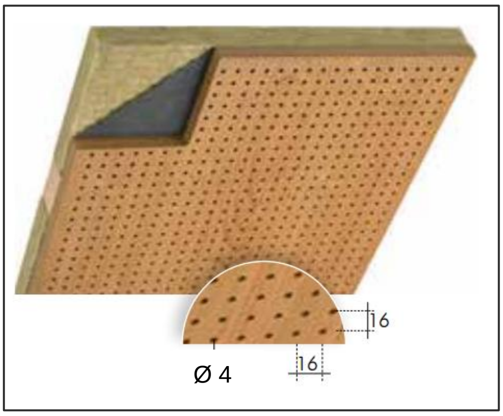


Figure 5.2 - Dimensions of the acoustic ceiling tile

The total surface of the ceiling that needs to be covered with the tiles can be seen in figure 5.3. This surface is the surface where the sound will reflect first and where the absorptive panels used to be. Different manufacturers make the tiles in different dimensions. The ceiling tiles for the edges can be custom made.

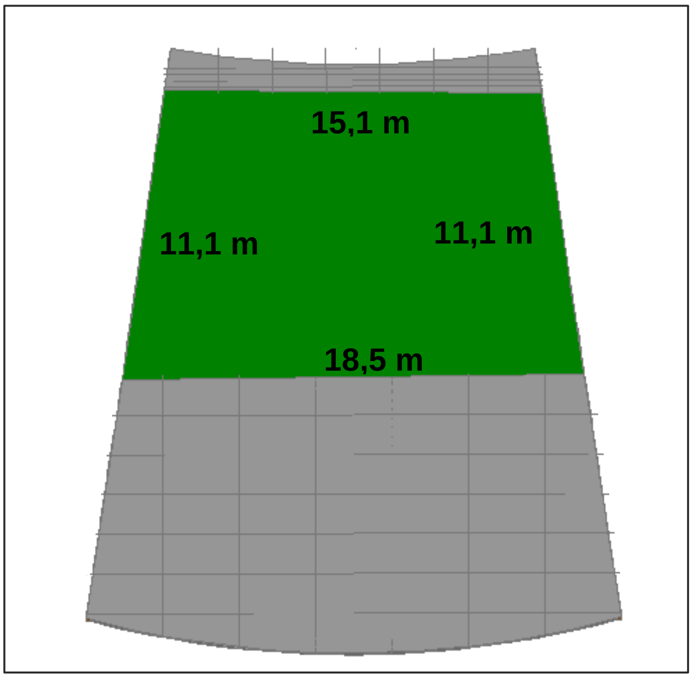
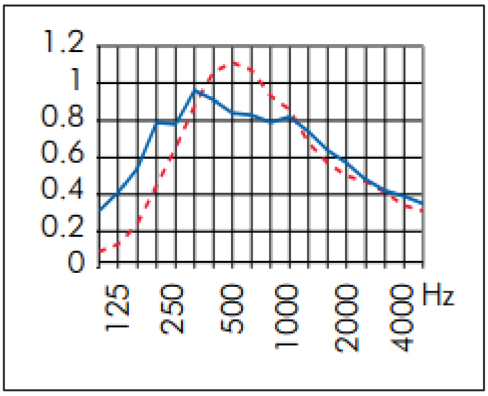


Figure 5.3 - Surface of the perforated acoustic tiles

The acoustic absorption coefficient depends on the air gap between the panel and the ceiling. The plenum for the Aula Magna is 600 mm. There is in the current state of the hall already a ceiling with a plenum of 600 mm, this value cannot be lowered because in this plenum installations are placed. Graph 5.2 shows in blue the acoustic absorption coefficient for the perforated acoustic panel [35]. The NRC of this element is 0,75.



Graph 5.2 - Sound absorption coefficients for the acoustic ceiling tile

Table 5.1 - Acoustic absorption coefficients of the absorbent side of the acoustic ceiling tile

	63 Hz	125 Hz	250 Hz	500 Hz	1K Hz	2K Hz	4K Hz	8K Hz
ceiling tile (absorbent side)	0,40	0,40	0,85	0,90	0,80	0,45	0,37	0,37

5.3.3 Installation of acoustic panels

Before placing the acoustic panels they need to be stored in the space where they are going to be installed for minimum two days. By doing this the wood can acclimatize to the room's temperature and humidity. Furthermore acoustic panels can expand if the conditions in the room change. It is important to have a dilatation joint between the perimeter of the wooden panels and the walls or other fixed objects.

Assembling the panelling and fixing it to the ceiling is executed with metallic profiles. With the square lay in system. By using this system the panels can be taken out and turned over in order to use the other side, when there is a chamber music performance.

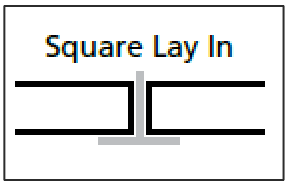


Figure 5.4 - Suspension system

5.3.4 Results using room acoustics software (Odeon)

In the 3D model that is adjusted to the reality the ceiling tiles can be added. The materials sound absorption coefficients are listed in table 5.1. The room acoustics software Odeon can calculate[6] the acoustic parameters of the space as if the acoustic tiles were placed. In Odeon results are simulated for each measuring point. The parameters that are generated are EDT [s], T30 [s], SPL [dB], C80 [dB], D50 [-], Ts [ms], LF80 [-], SPL(A) [-], LG80* [-][7] and STI [-].

5.3.4.1 Comparing to the recommended values

The measured values are compared with the recommended values for a lecture hall that are presented in table 3.3 and with the values from before the panel was placed.

Speech intelligibility

The speech intelligibility is in every point higher than 0,50, the recommended value. As presented in the table below the values have improved after placing the ceiling tiles. The quality that correspondents to the STI values are listed in table 2.8.

Table 5.2 - Comparison STI before and after placing acoustic panel

	before placing acoustic tiles	after placing acoustic tiles
STI min	0,60 (good)	0,61 (good)
STI average	0,64 (good)	0,67 (good)
STI max	0,71 (good)	0,77 (excellent)

Definition

The definition has improved. Before placing the acoustic tiles 15 values of D50 were below 0,50%, after the improvement only three values are below 0,50%. These three values are all in

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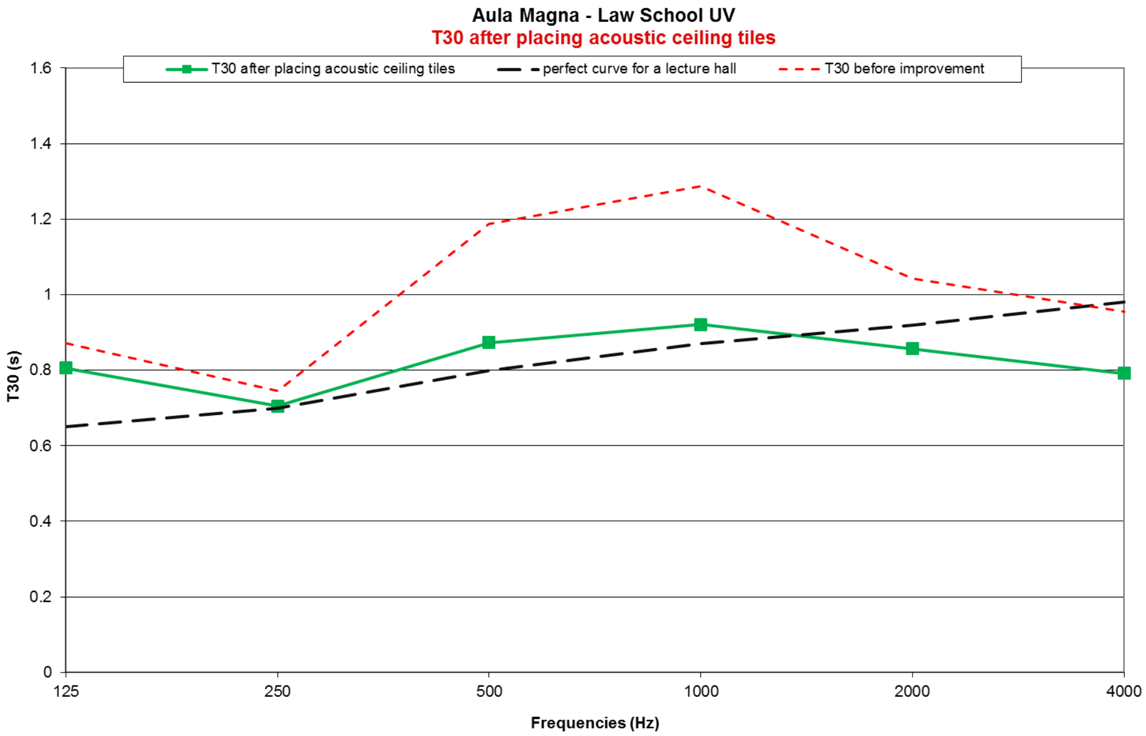
[6] Precision mode, impulse response length = 1500 ms.

[7] LG80* is the old name for $\mathrm{Lj(Average)}_{80}^{\infty}$

point 19 (for 500 Hz, 1000 Hz, 2000 Hz). Point 19 is near the wall and next to the door. Because they are all in the same point, the low results possibly results from the placement of the point in the model.

Reverberation time

In the graph below, the average T30 is shown before the improvement in red, the average T30 after improvement in green and in black the perfect curve for a lecture hall. The average reverberation time for the mid frequencies is 0,90 s. This is good for a lecture auditorium because the recommended value is between 0,7 s – 1,2 seconds. Before the improvement this was 1,24 seconds. This was too high for a good experience during an unamplified lecture.



Graph 5.3 - T30 after placing acoustic ceiling tiles

5.4 Improving the properties of the hall for a chamber music concert

5.4.1 Proposal for improvement for a chamber music performance

The reverberation time is too low and the reverberation time curve should be adjusted. The proposed ceiling tiles have two sides. One side is absorbent and is used in case of a lecture. The second side is reflective. Besides the reflective tiles, two reflective panels are placed on stage. These panels are movable and can be hidden behind the screen on stage or in a storage nearby. The scaffold is also removed to make place for the musicians.

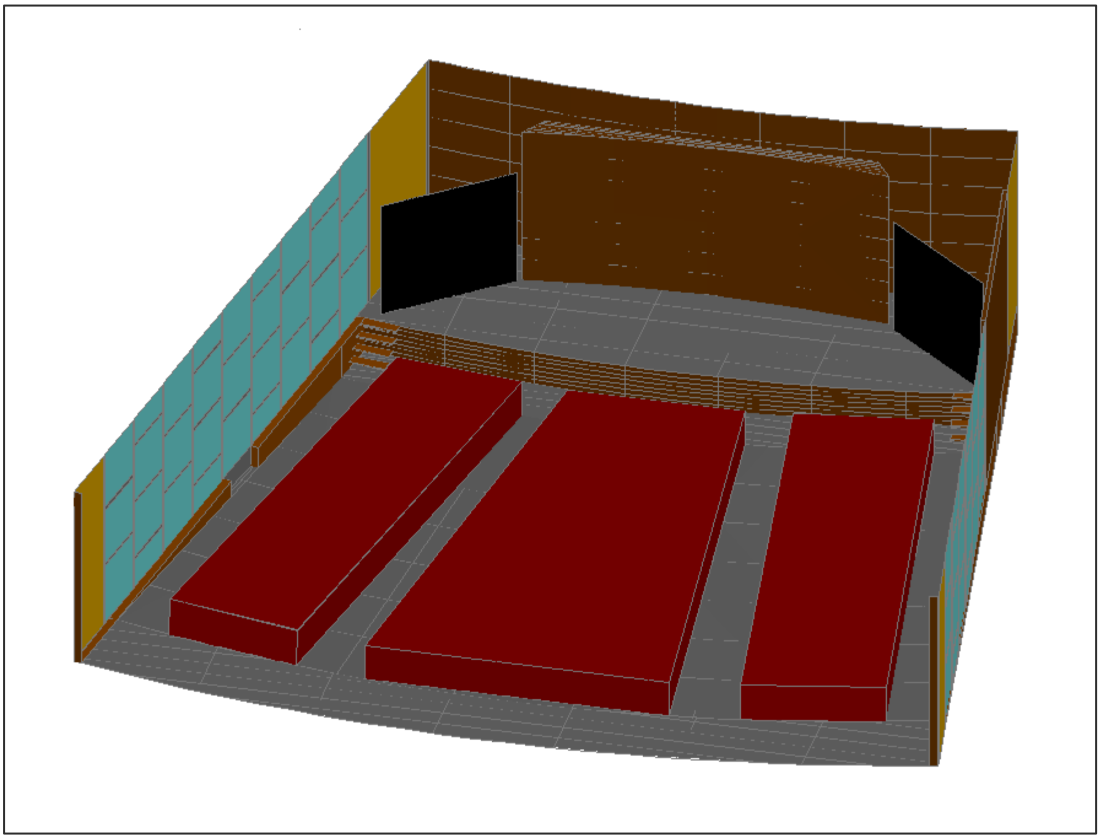


Figure 5.5 - 3D model with proposal for improvements chamber music concert

5.4.2 Properties of the acoustic tile – side 2

The reflective side of the tile is composed of 10 mm thick plasterboard finished with a rough plaster. This material has sound absorption coefficients listed in table 5.3 [36]. The surface where the ceiling tiles are used is the same as the absorbent tiles. The NRC of this element is 0,063.

Table 5.3 - Acoustic absorption coefficients of the reflective side of the acoustic ceiling tile

	63 Hz	125 Hz	250 Hz	500 Hz	1K Hz	2K Hz	4K Hz	8K Hz
ceiling tile (reflective side)	0,02	0,02	0,02	0,08	0,10	0,05	0,05	0,05

5.4.3 Properties of the movable panels

The panels are 3,7 m wide and 3,5 m high. The panels are made of 70 mm plywood panel covered with rough plaster. The sound absorption coefficients are listed in table 5.3. The panels can be fitted with wheels making it easier to move them around. If they are stored behind the screen, it will not interfere with the properties of the hall during a lecture.

5.4.3.1 Results using room acoustics software (Odeon)

The measured values can be compared with the recommended values listed in table 3.3.

Reverberation time

The curve of the reverberation time before any improvements has low values in the bass frequencies. For a musical performance these need to be high. By adding reflective ceiling tiles and movable reflective panels the bass frequencies stay longer in the room, resulting in a higher reverberation time. The average reverberation time for the mid frequencies after the improvements is 1,07 seconds. This is the minimum for a chamber music concert. The Aula Magna of the Faculty of Law is a small hall. Values that are found in studies (such as the study from Beranek) are for large concert halls. These halls are often ten times bigger. Therefore it is acceptable that the recommended reverberation time for mid frequencies chamber music is around 1,0 – 1,5 seconds.

In the graph below it is clear that the new reverberation curve (in green) is more like the perfect one (in black) than the reverberation time curve before any alterations (in red).

Graph 5.4 - T30 after placing acoustic ceiling tile and movable panels

Warmth

Warmth is measured with the bass ratio, as seen in the theoretical chapter (formula 2.6).

$$\mathrm{BR} = \frac{\mathrm{T}_{60}(125) + \mathrm{T}_{60}(250)}{\mathrm{T}_{60}(500) + \mathrm{T}_{60}(1000)} = \frac{1.24\ \mathrm{s}\ +\ 1.01\ \mathrm{s}}{1.06\ \mathrm{s}\ + 1.04\ \mathrm{s}} = 1.1$$

It is recommended that this value is between 1,1 and 1,45 for playing chamber music. By adding the ceiling tiles and the reflective panels the bass ratio is now good. Before the alteration the bass ratio was 0,92.

Brilliance

The brilliance ratio is used to quantify the brilliance, as seen in the theoretical chapter (formula 2.7).

$$\mathrm{br} = \frac{\mathrm{T}_{60}(2000) + \mathrm{T}_{60}(4000)}{\mathrm{T}_{60}(500) + \mathrm{T}_{60}(1000)} = \frac{0.99\ \mathrm{s}\ +\ 0.89\ \mathrm{s}}{1.06\ \mathrm{s}\ + 1.04\ \mathrm{s}} = 0{,}88$$

The brilliance ratio should be higher than 0,85 when there is chamber music played. After adding the ceiling tiles and reflective panels the brilliance ratio is 0,88. In the current state of the hall the brilliance ratio is 0,83.

6 Conclusions

6.1 Current state of the Aula Magna of the Faculty of Law

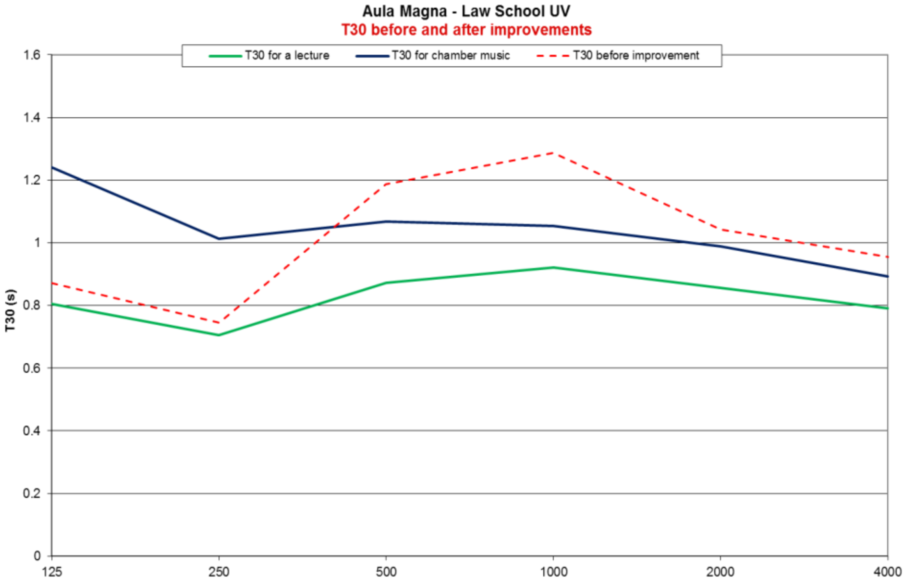
The Aula Magna of the Faculty of Law does not have the optimal properties for a lecture or for a chamber music performance. Therefore alterations are needed. A big problem of the hall is that the last rows don't have a good view at the stage. This could be solved by increasing the inclinations of the seats. This would also improve the speech intelligibility because understanding and seeing a person are correlated.

6.2 Proposal for improvements

Over the surface where the first reflections hit and straight above the stage, double-sided ceiling tiles will be placed. One side is absorbent and the other side reflective. When there is a lecture the absorbent side is used. This is done to lower the average reverberation time and to lower the reverberation time of the lower frequencies. The reverberation time of the higher frequencies should be higher in a perfect situation, but the proposal for improvements will lead to a big enhancement during a lecture nevertheless.

When there is a chamber music performance all the ceiling tiles are turned, so that the reflective side is used. Furthermore the scaffold is removed and two reflective panels are placed on the stage. The effect is that the reverberation time curve will be more similar to the perfect curve for a chamber music performance. It is important that the reverberation time of the bass frequencies is higher than the reverberation time of the other frequencies. This was definitely not the case before the improvement. This new curve has a brilliance ratio and bass ratio in line with the recommended values.

This proposal is feasible and easy to install and use. The two movable panels can be stored behind the screen on stage. Therefore no storage space is needed. These simple measures will undoubtedly improve the experience for the audience.



Graph 6.1 - T30 before and after improvements

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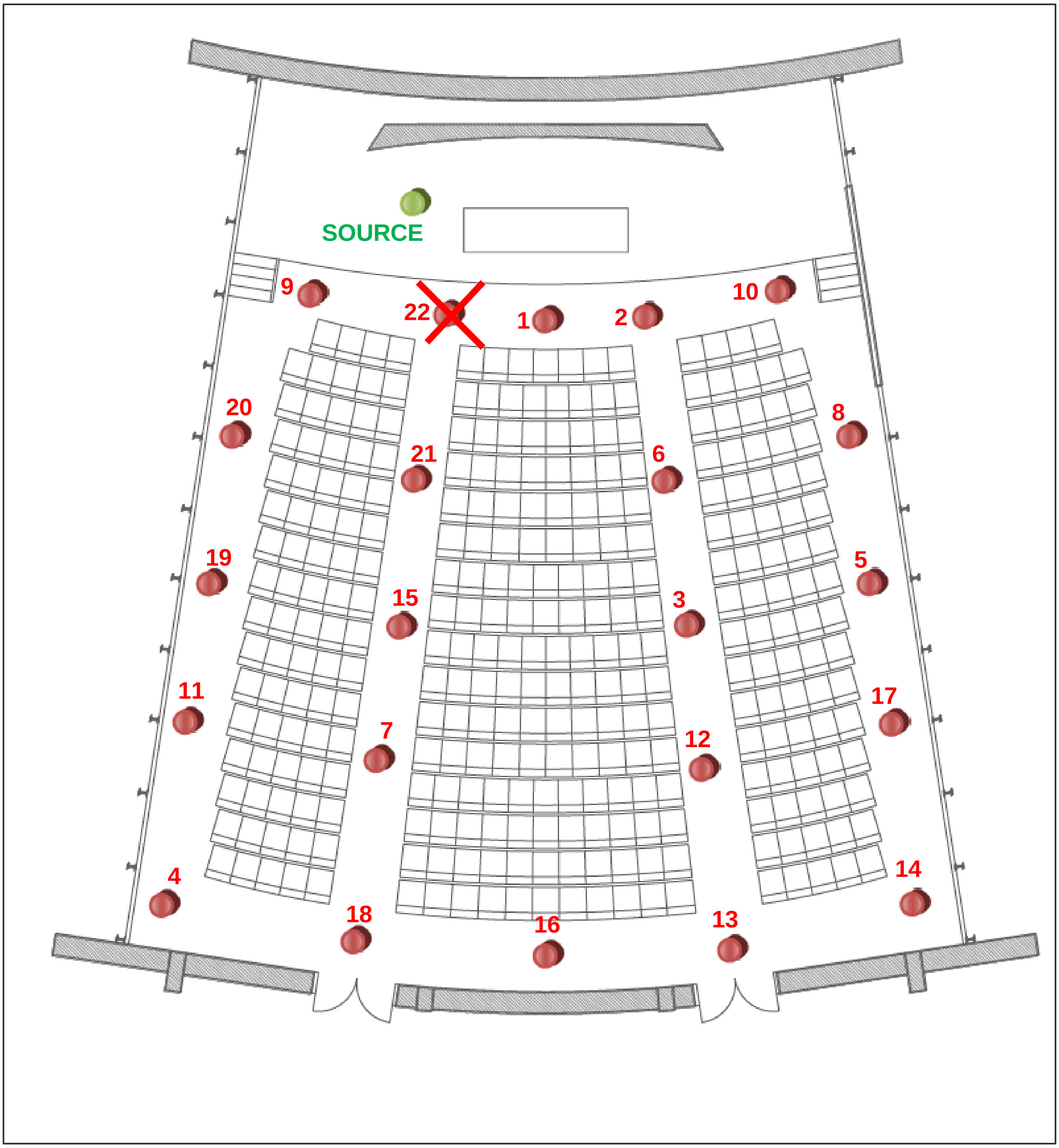
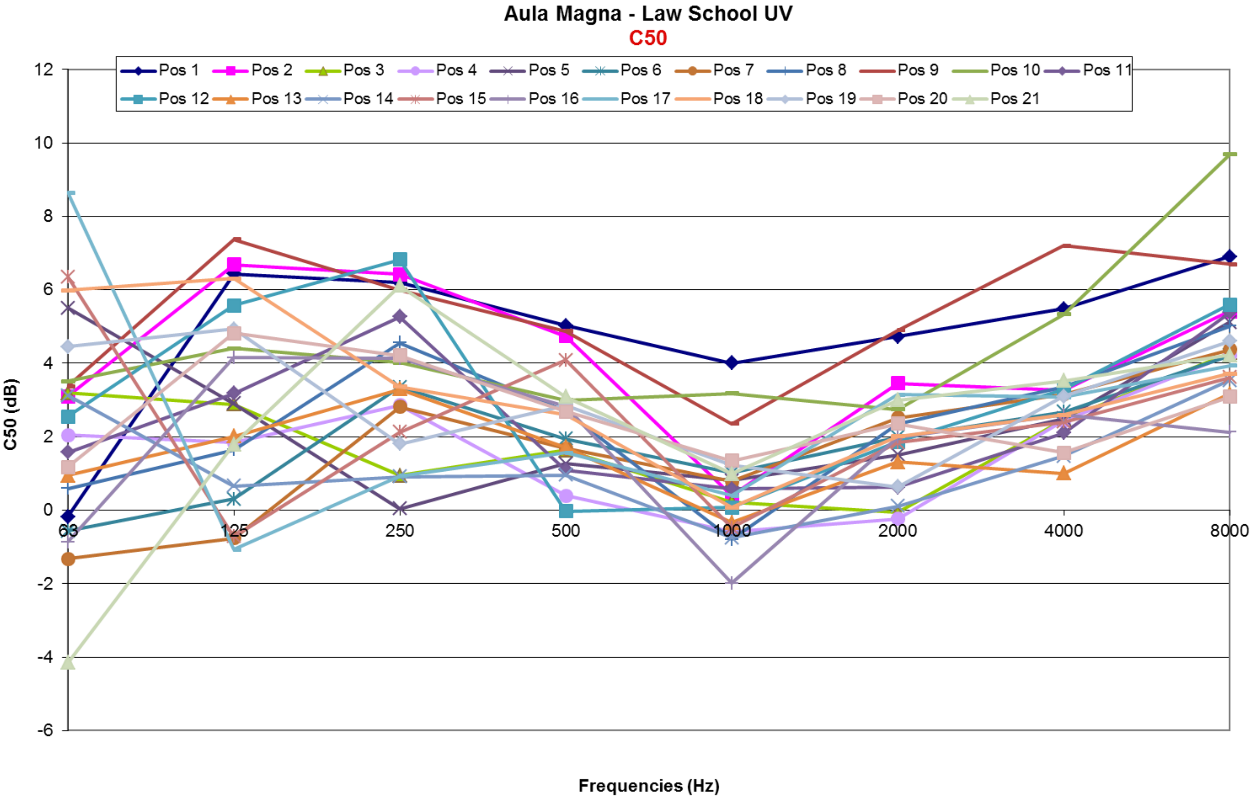
Annexes

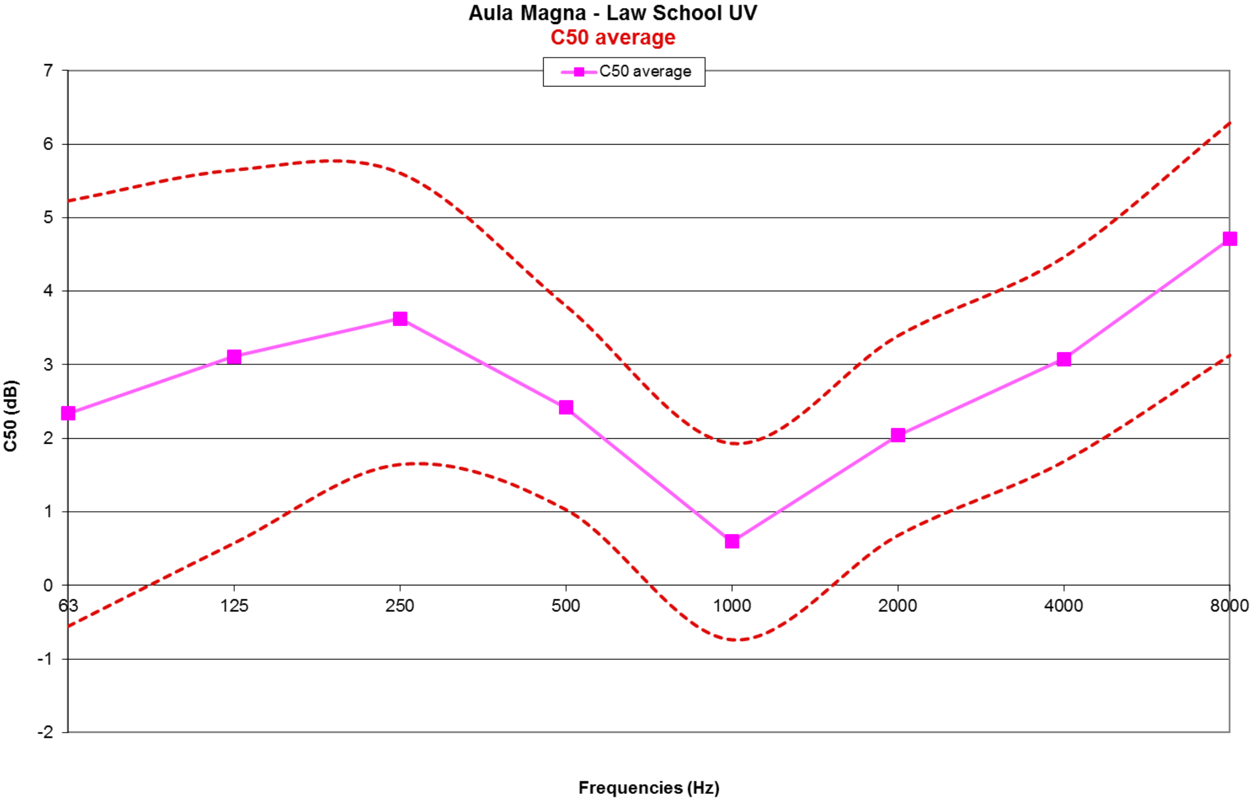
Annex 1 – Numbering of the measuring points



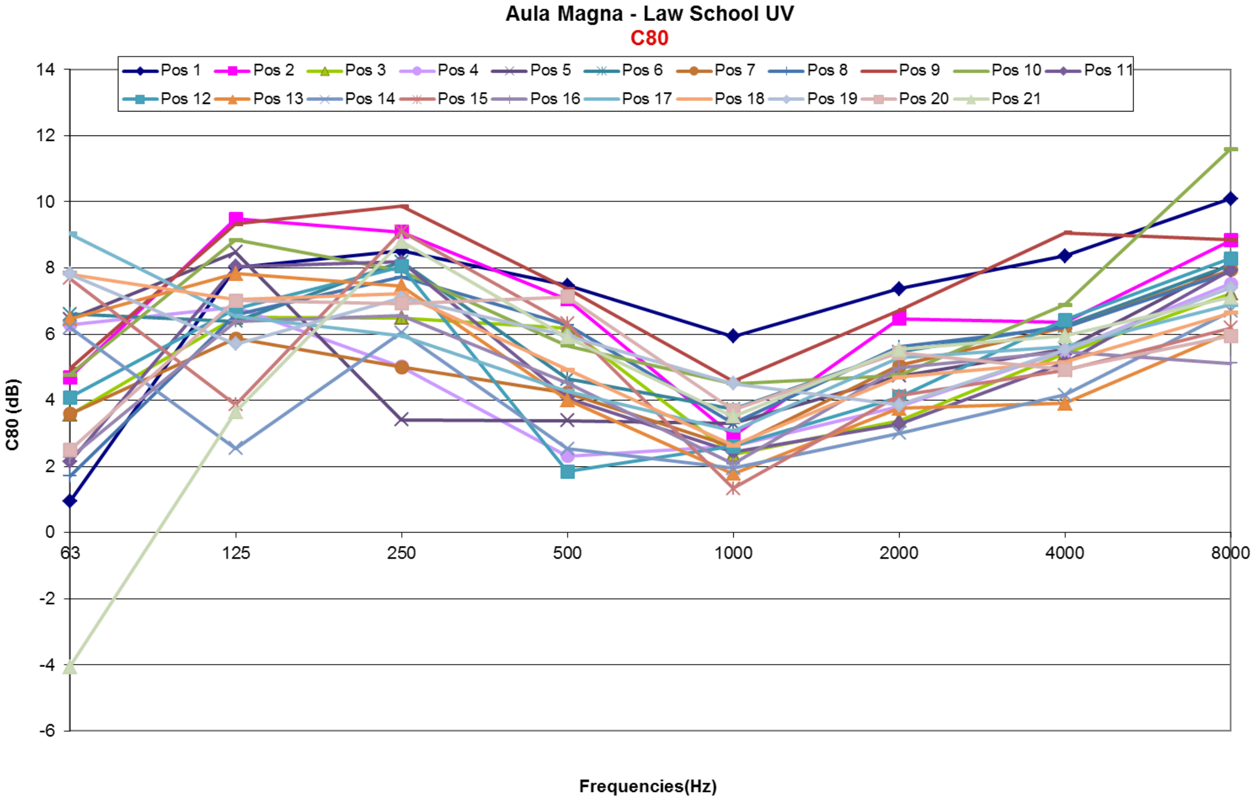
Annex 2 – Acoustic parameters: the measurements *in situ* in graphs

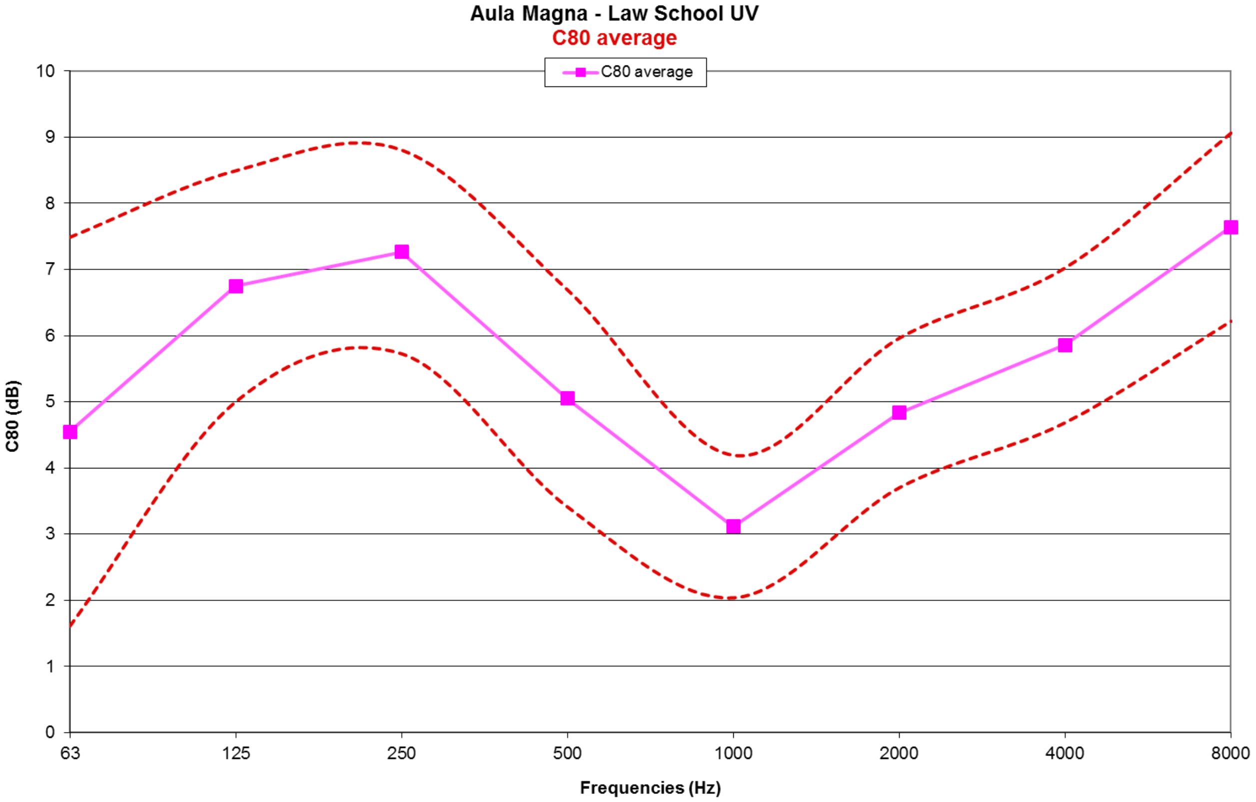
C50



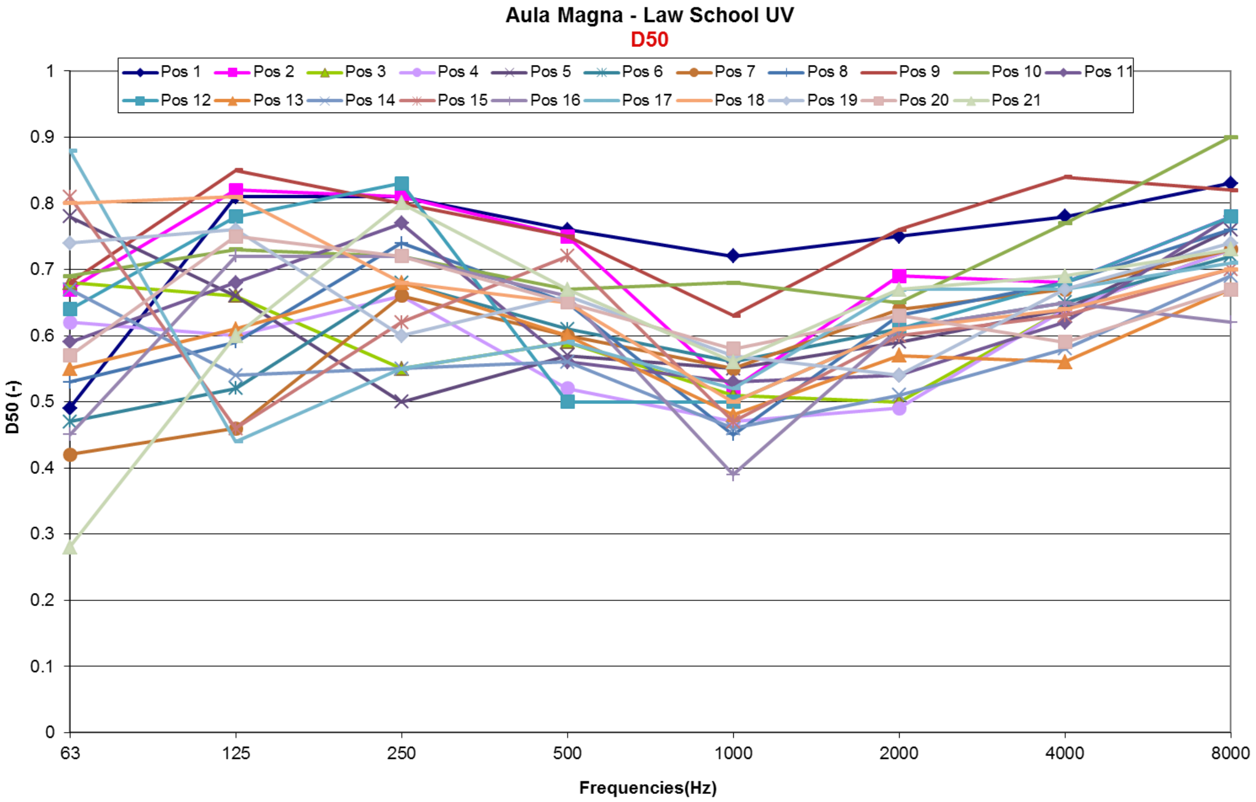


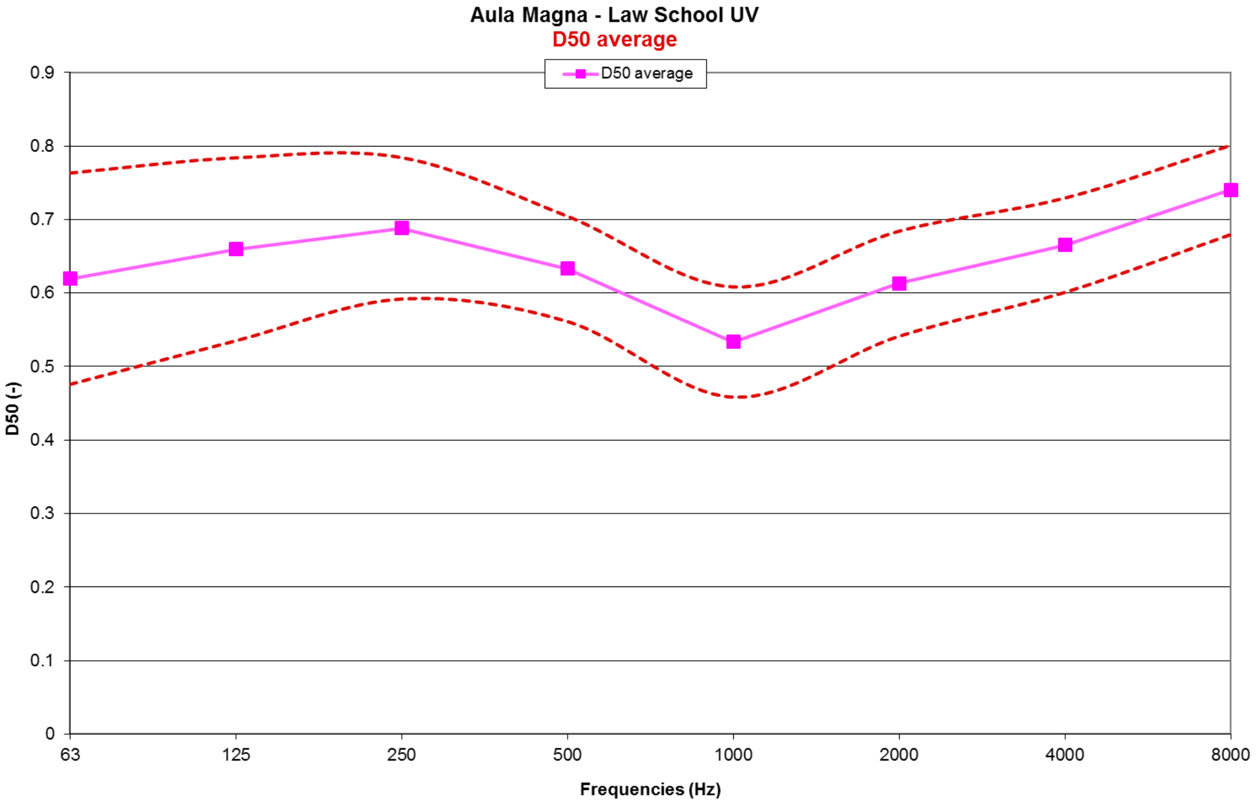
C80


Aula Magna - Law School UV
C80
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
C80 (dB)
14
12
10
8
6
4
2
0
-2
-4
-6
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)

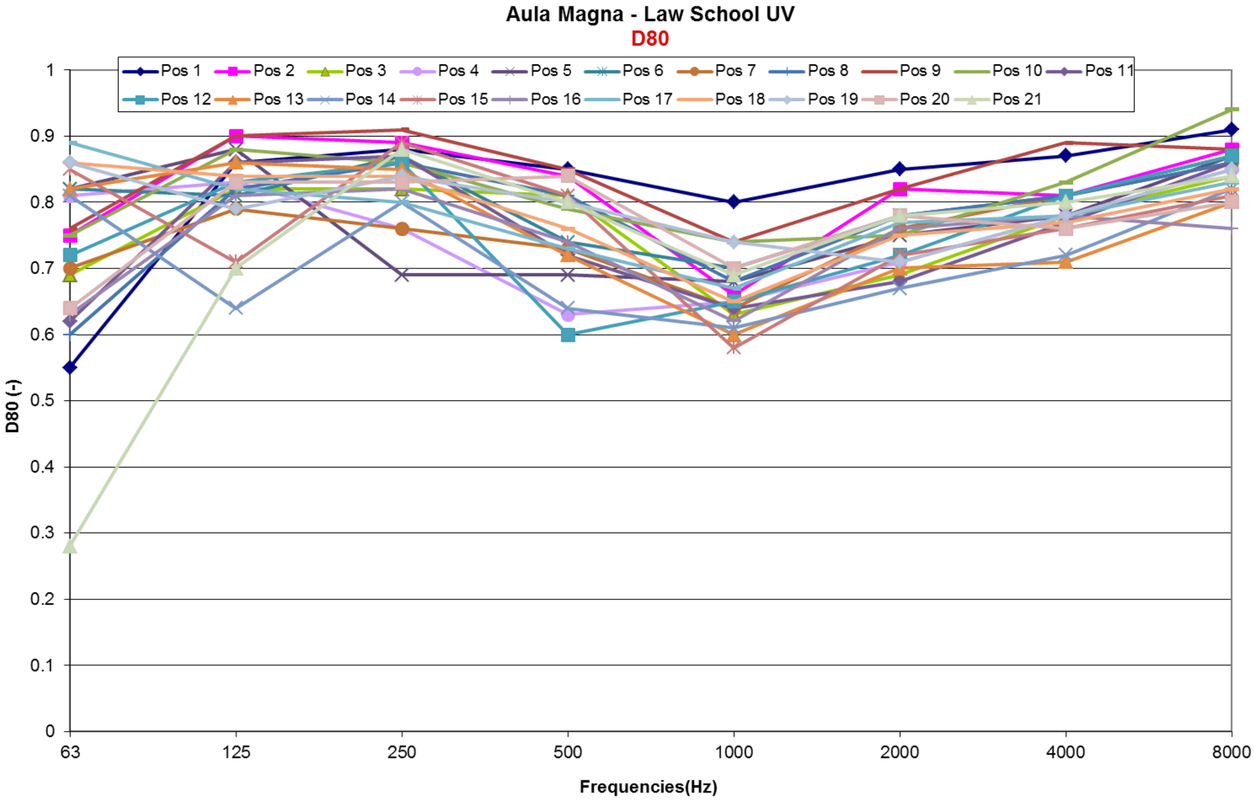

Aula Magna - Law School UV
C80 average
C80 average
C80 (dB)
10
9
8
7
6
5
4
3
2
1
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

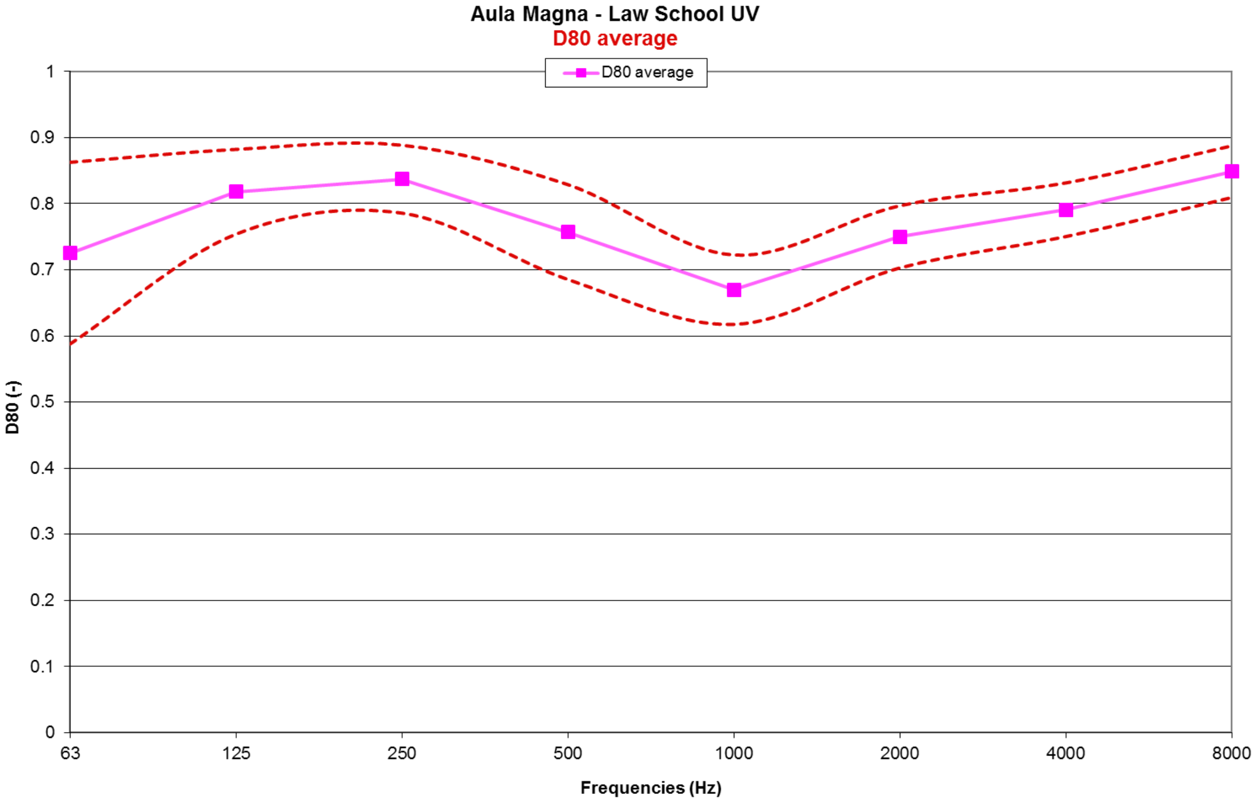
D50


Aula Magna - Law School UV
D50
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
D50 (-)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)

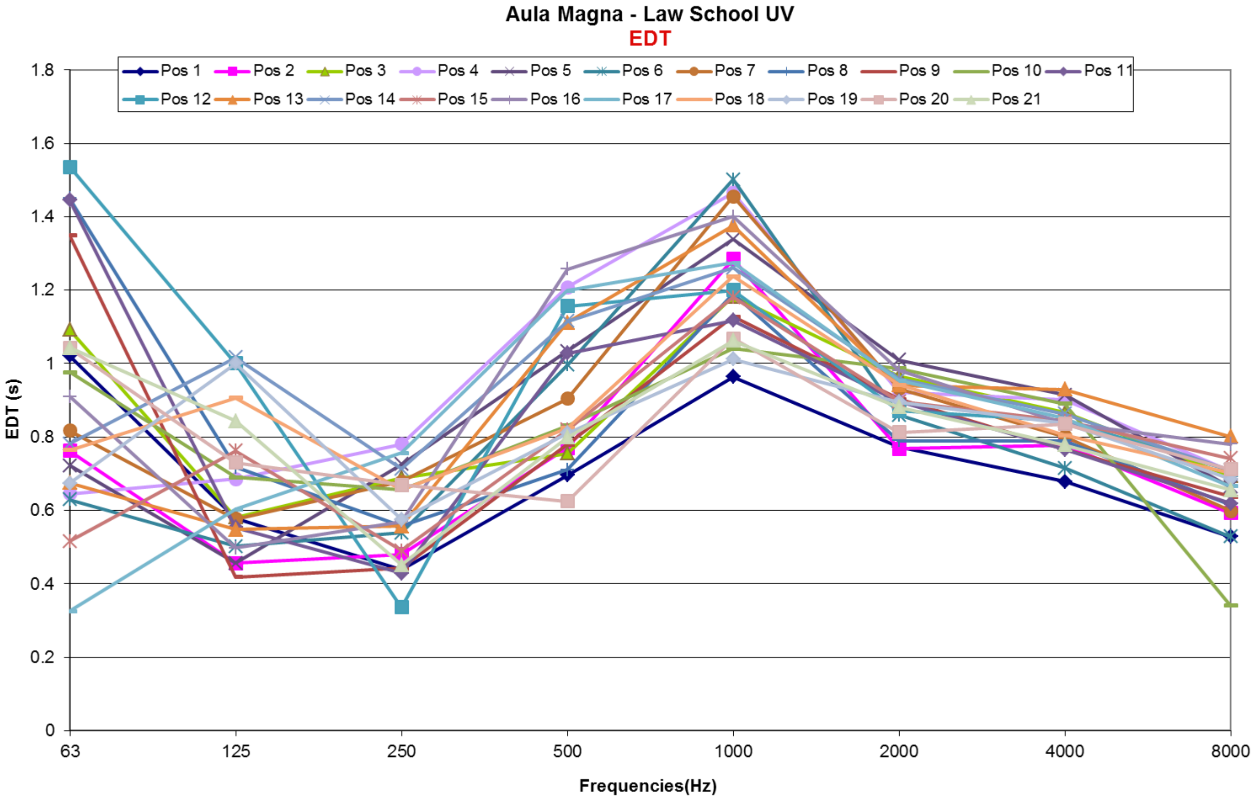

Aula Magna - Law School UV
D50 average
D50 average
D50 (-)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

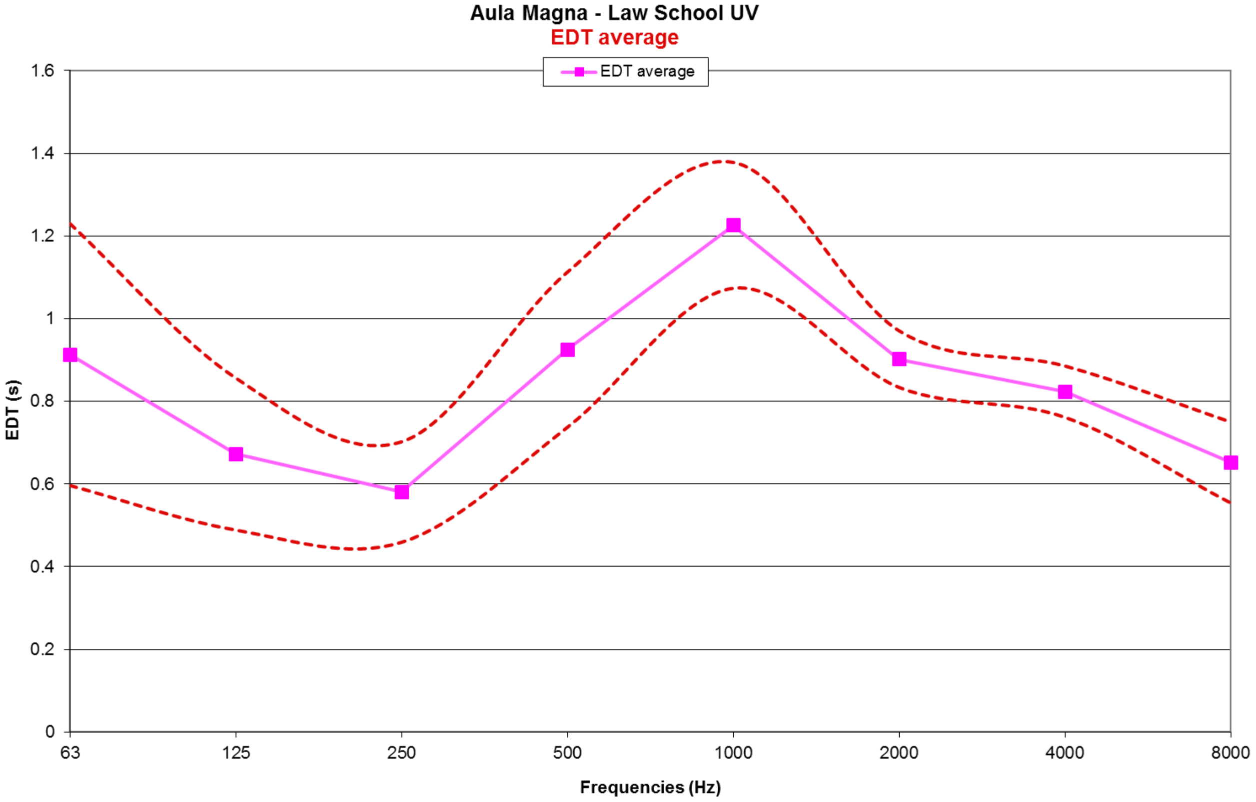
D80


Aula Magna - Law School UV
D80
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
D80 (-)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)

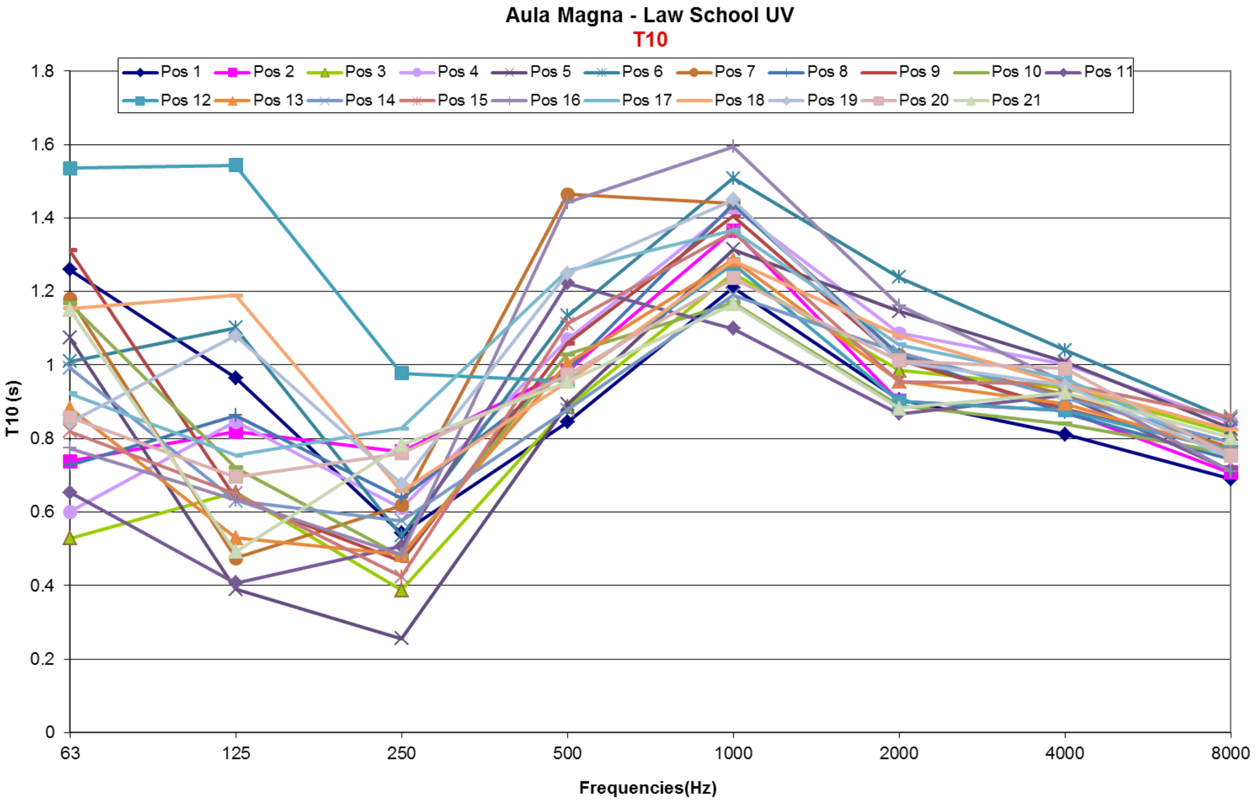

Aula Magna - Law School UV
D80 average
D80 average
D80 (-)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

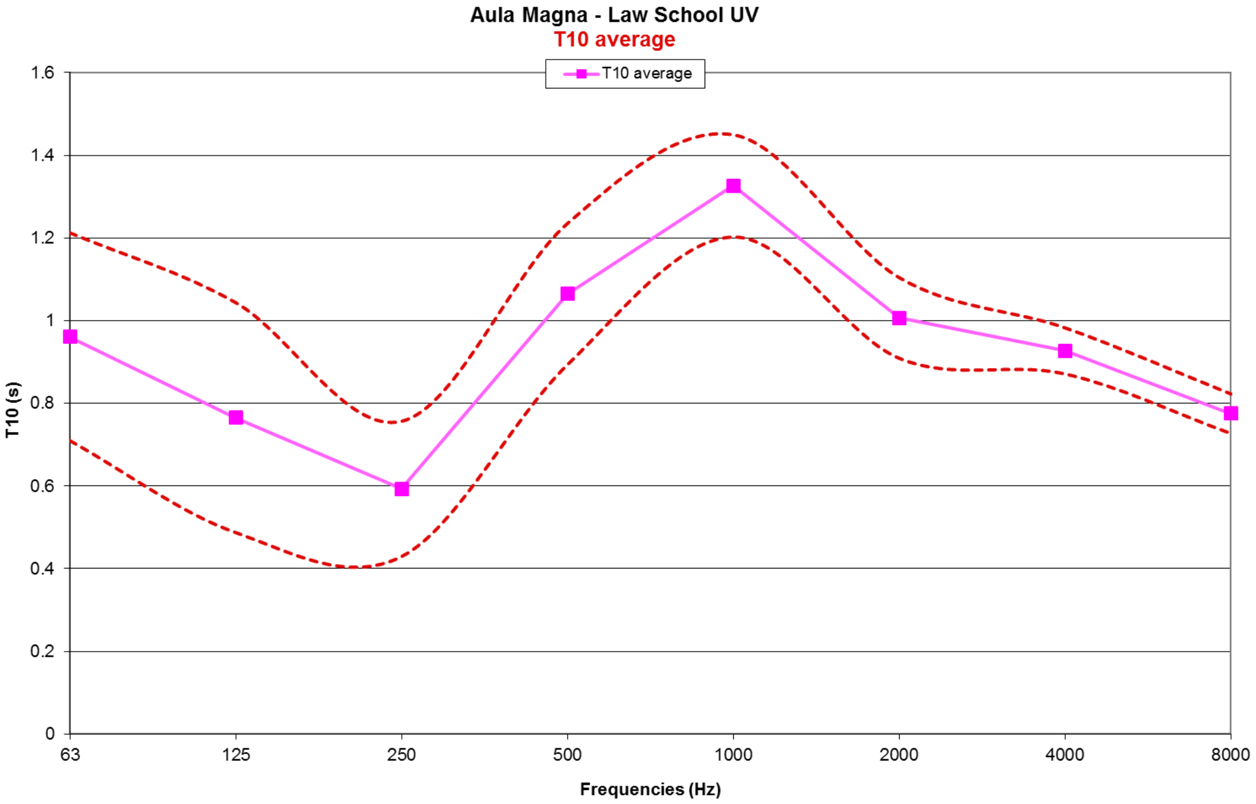
EDT


Aula Magna - Law School UV
EDT
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
EDT (s)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)

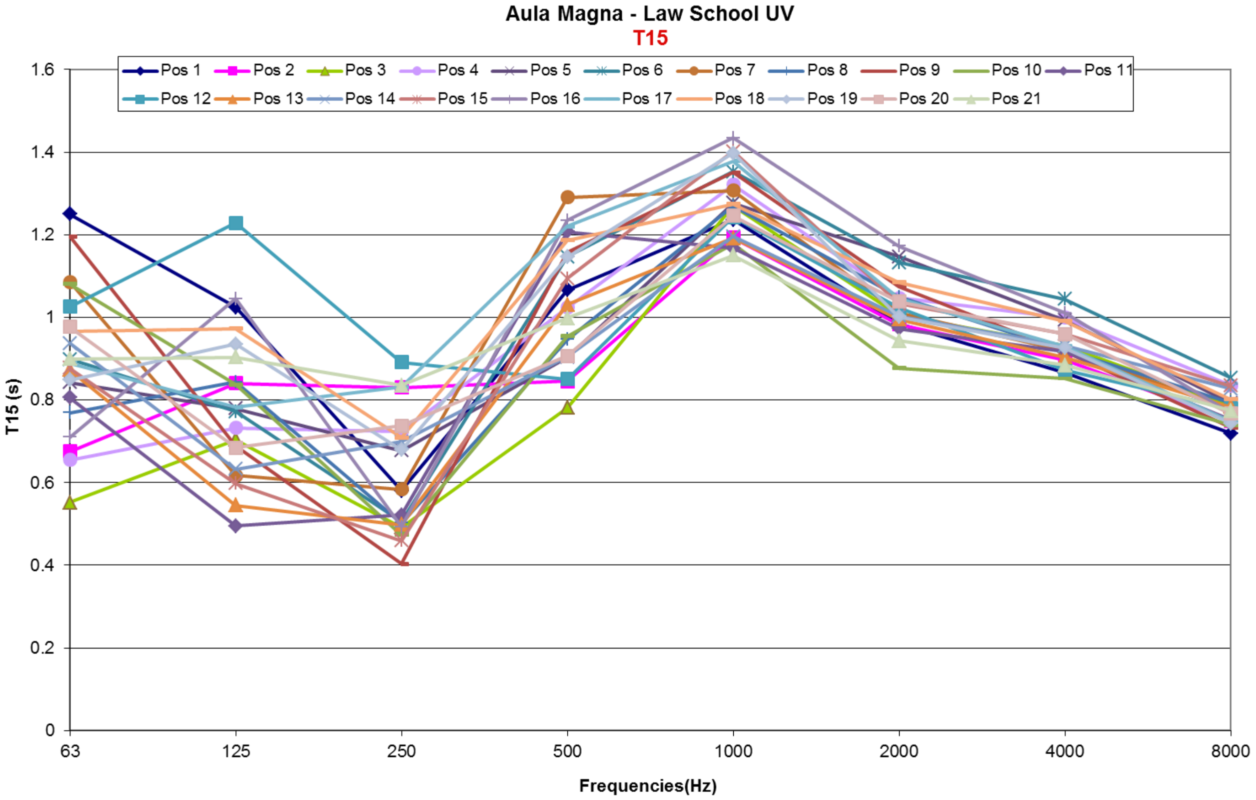

Aula Magna - Law School UV
EDT average
EDT average
EDT (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

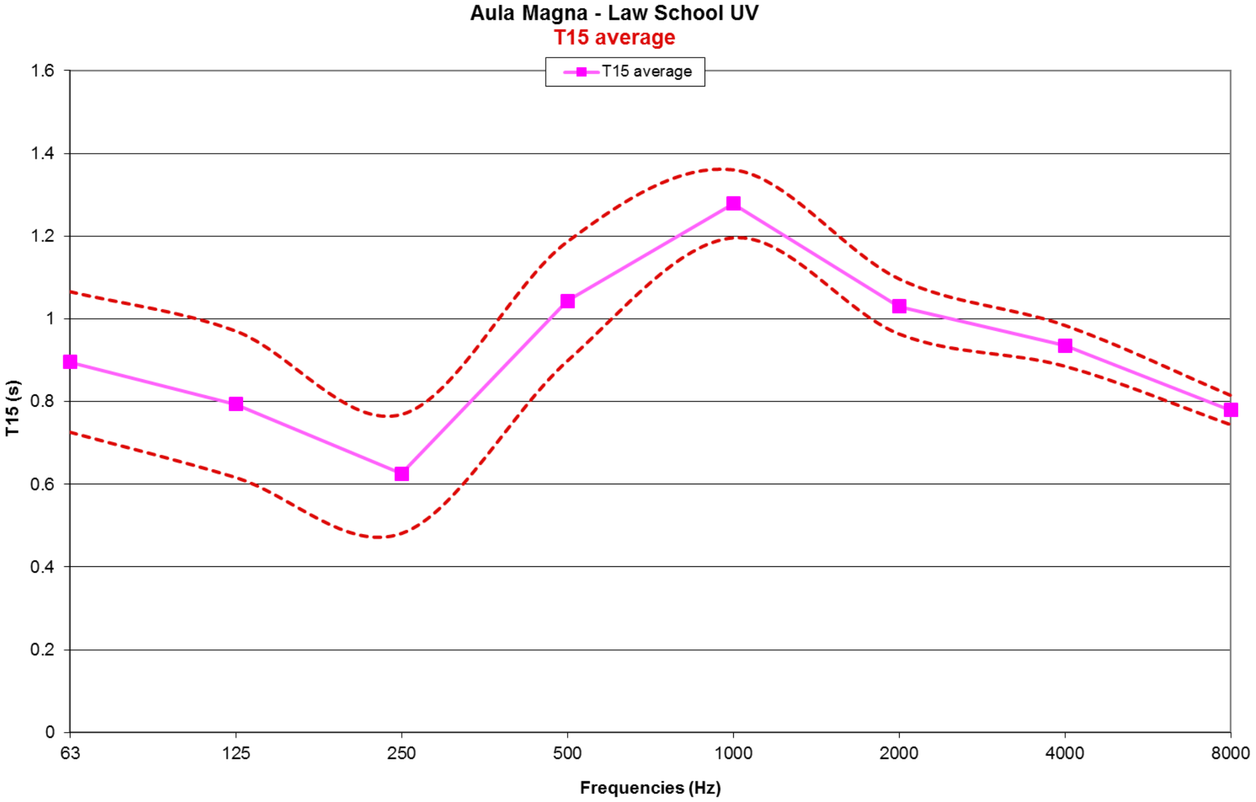
T10


Aula Magna - Law School UV
T10
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
T10 (s)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)

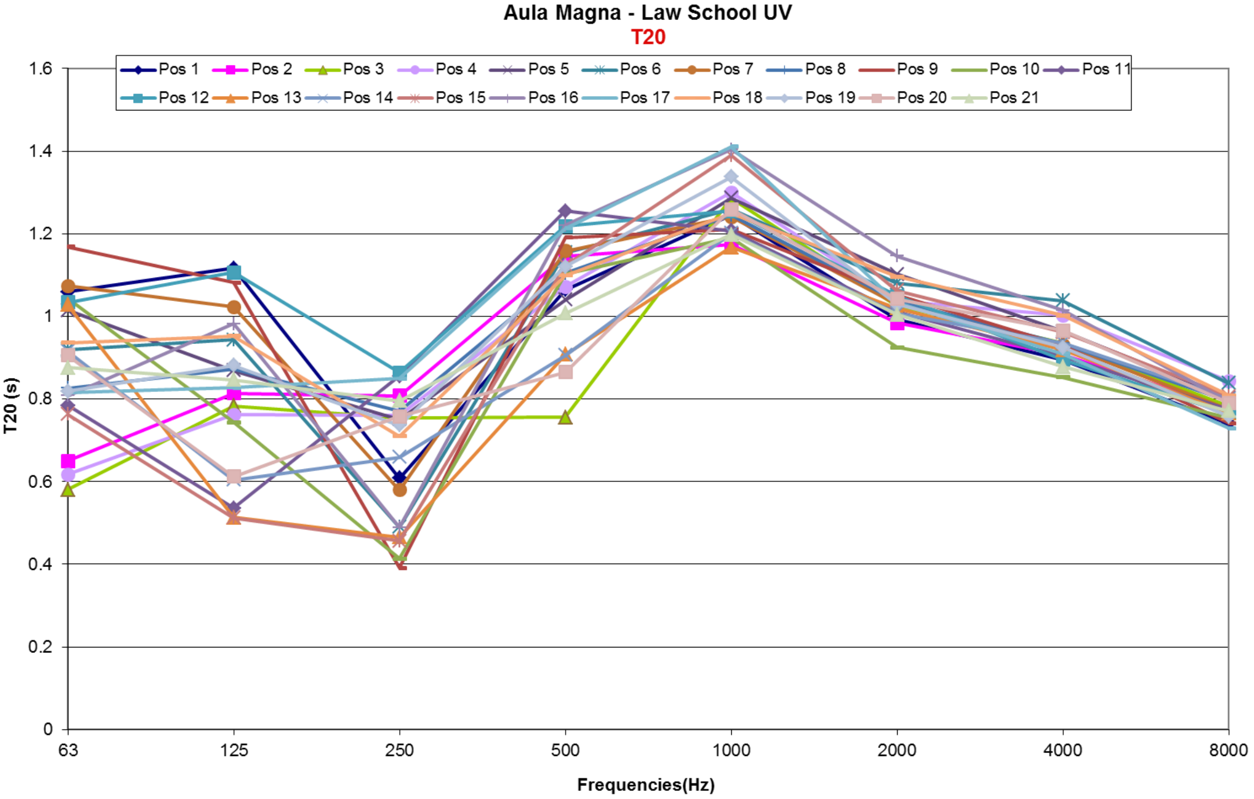

Aula Magna - Law School UV
T10 average
T10 average
T10 (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

T15

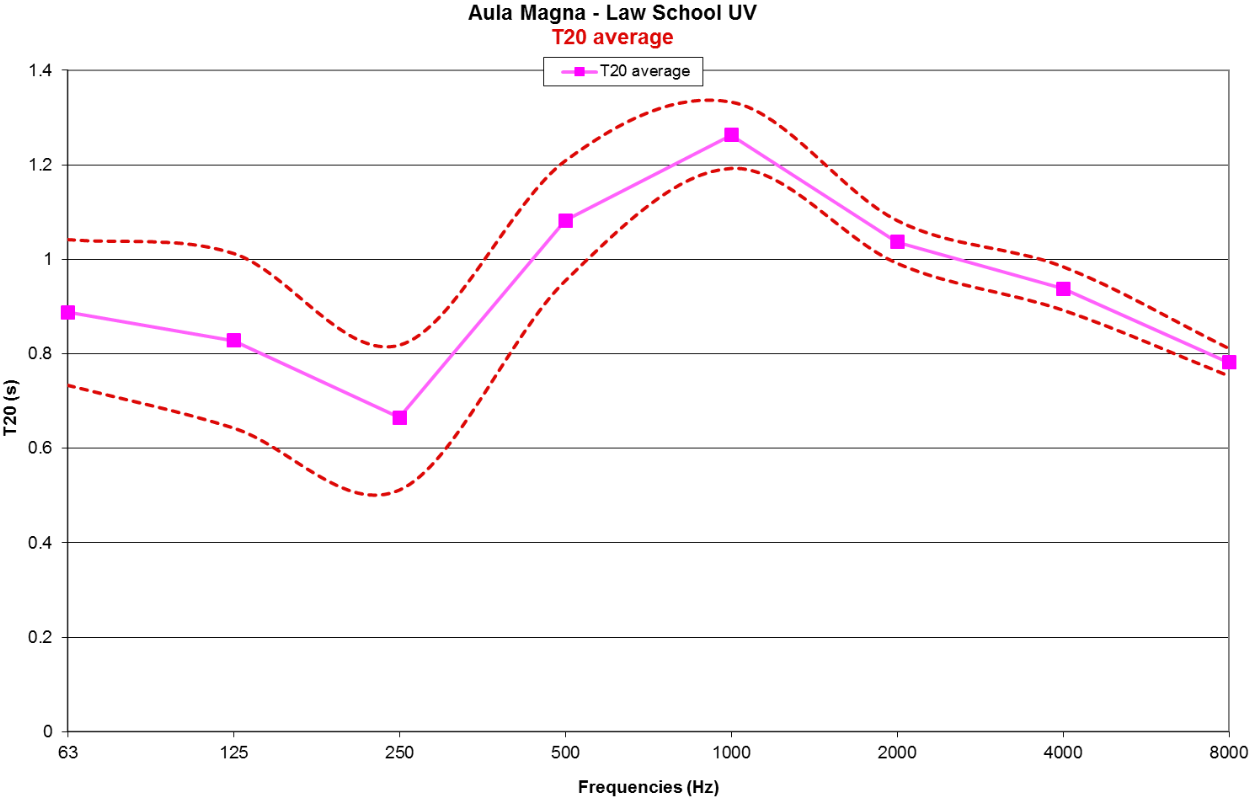

Aula Magna - Law School UV
T15
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
T15 (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)


Aula Magna - Law School UV
T15 average
T15 average
T15 (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

T20

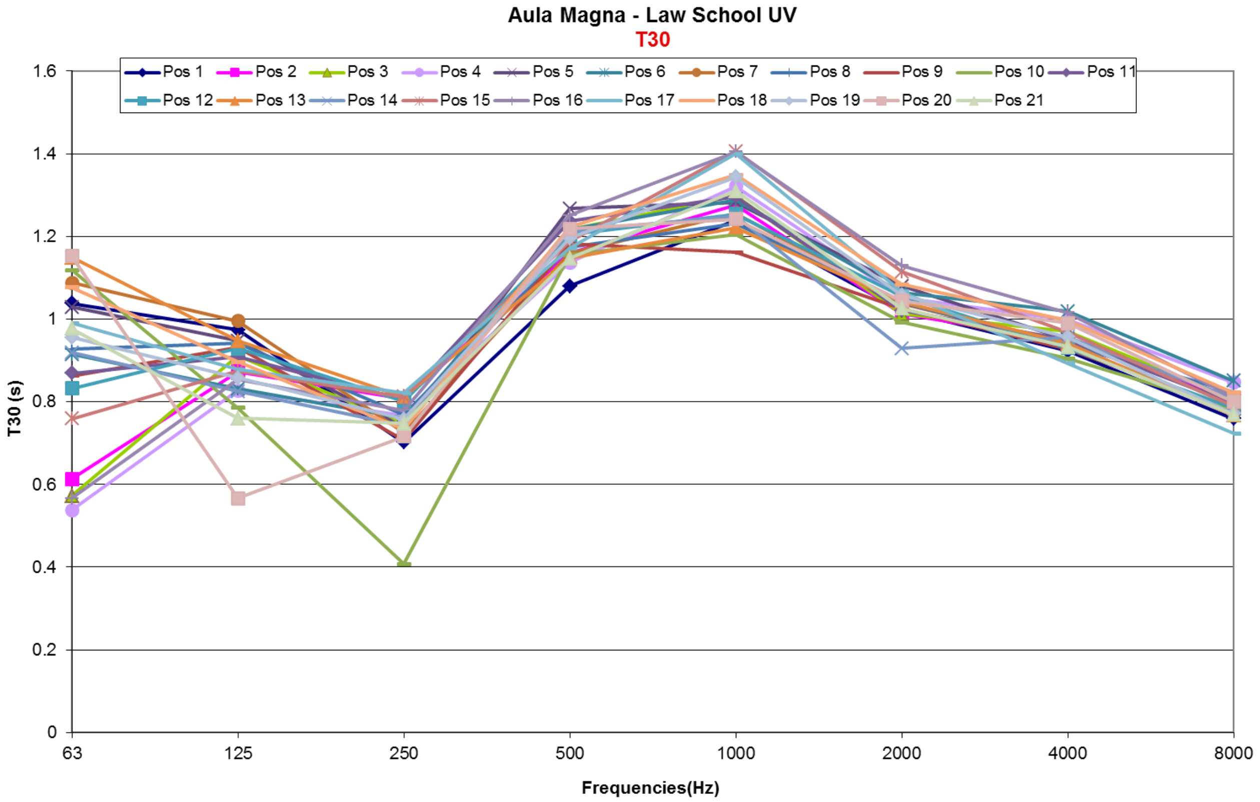


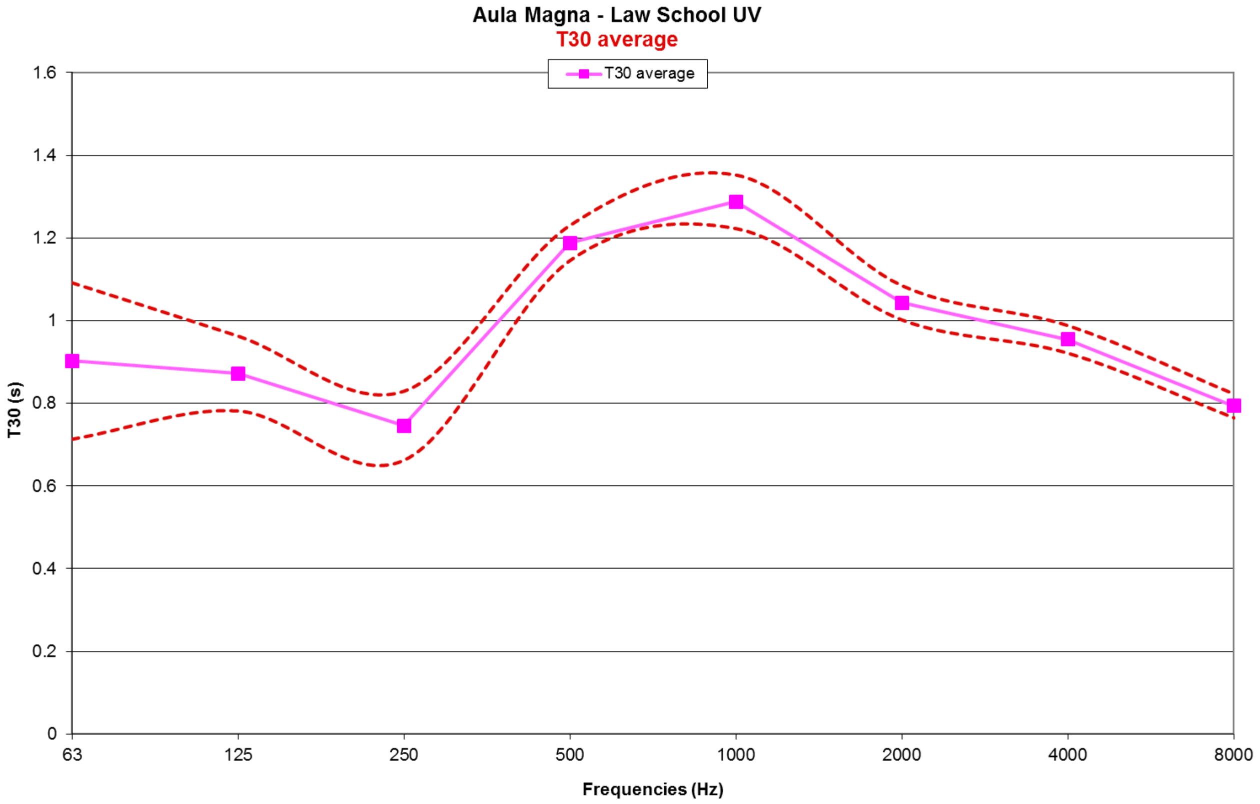
Aula Magna - Law School UV
T20
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
T20 (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)



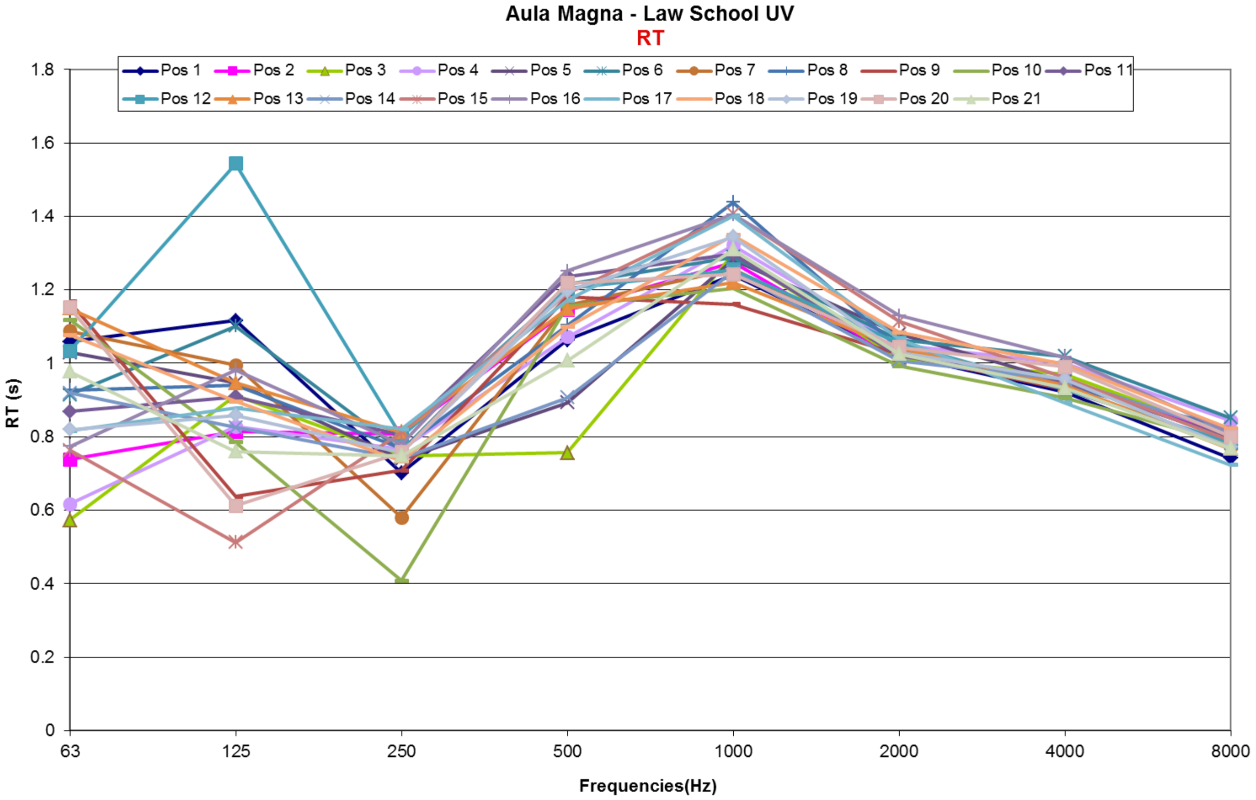
Aula Magna - Law School UV
T20 average
T20 average
T20 (s)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

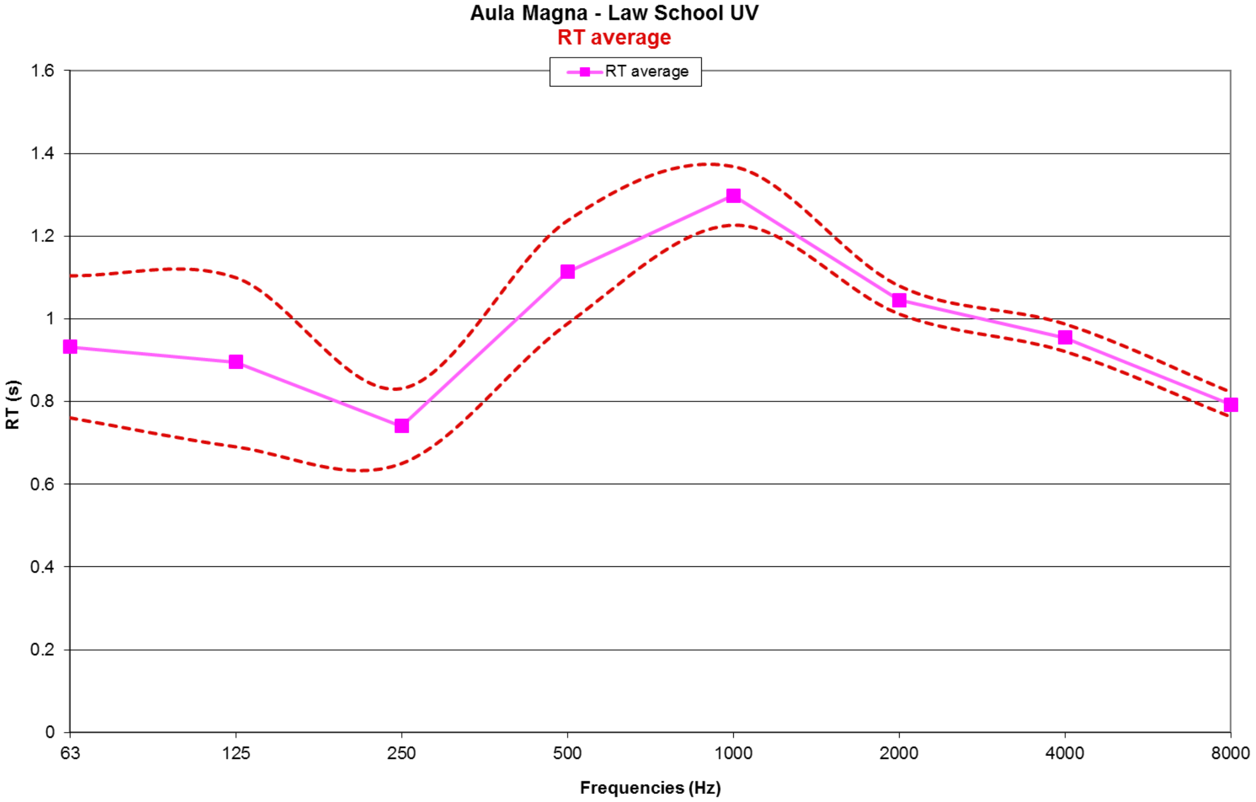
T30


Aula Magna - Law School UV
T30
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
T30 (s)
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)


Aula Magna - Law School UV
T30 average
T30 average
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
T30 (s)
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

RT


Aula Magna - Law School UV
RT
Pos 1
Pos 2
Pos 3
Pos 4
Pos 5
Pos 6
Pos 7
Pos 8
Pos 9
Pos 10
Pos 11
Pos 12
Pos 13
Pos 14
Pos 15
Pos 16
Pos 17
Pos 18
Pos 19
Pos 20
Pos 21
RT (s)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies(Hz)

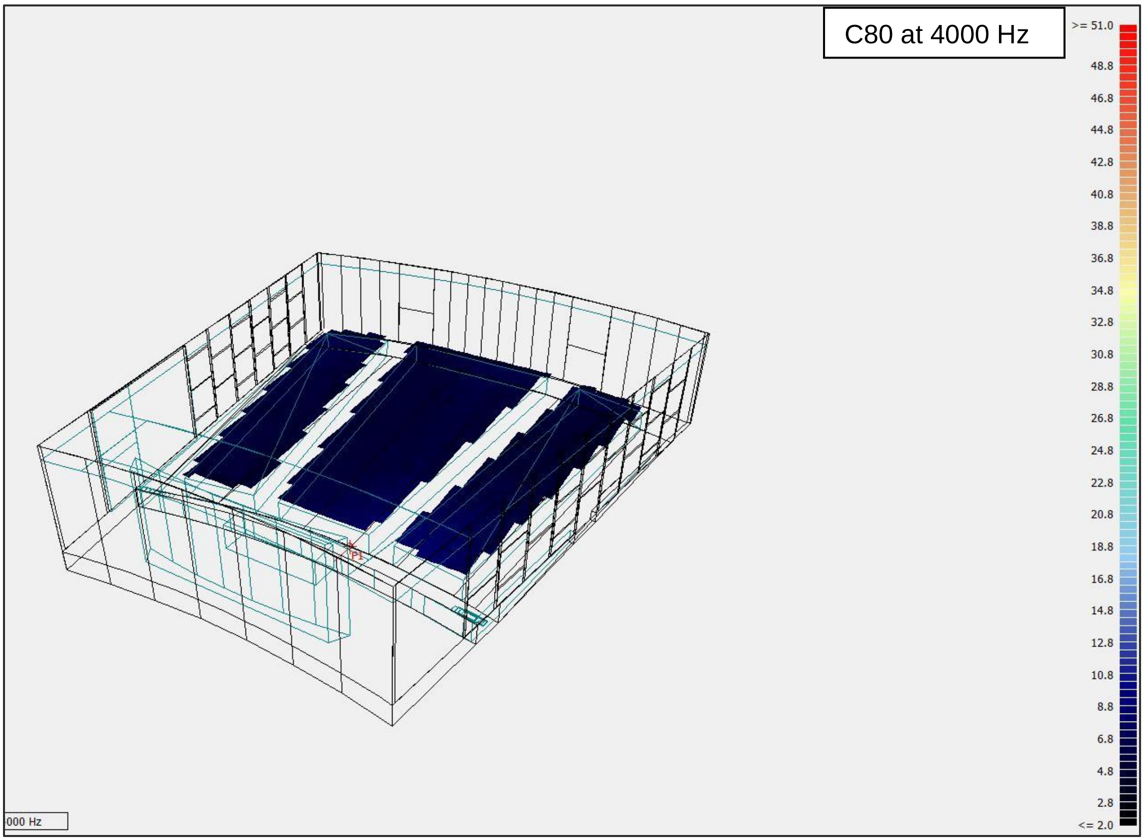

Aula Magna - Law School UV
RT average
RT average
RT (s)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
63
125
250
500
1000
2000
4000
8000
Frequencies (Hz)

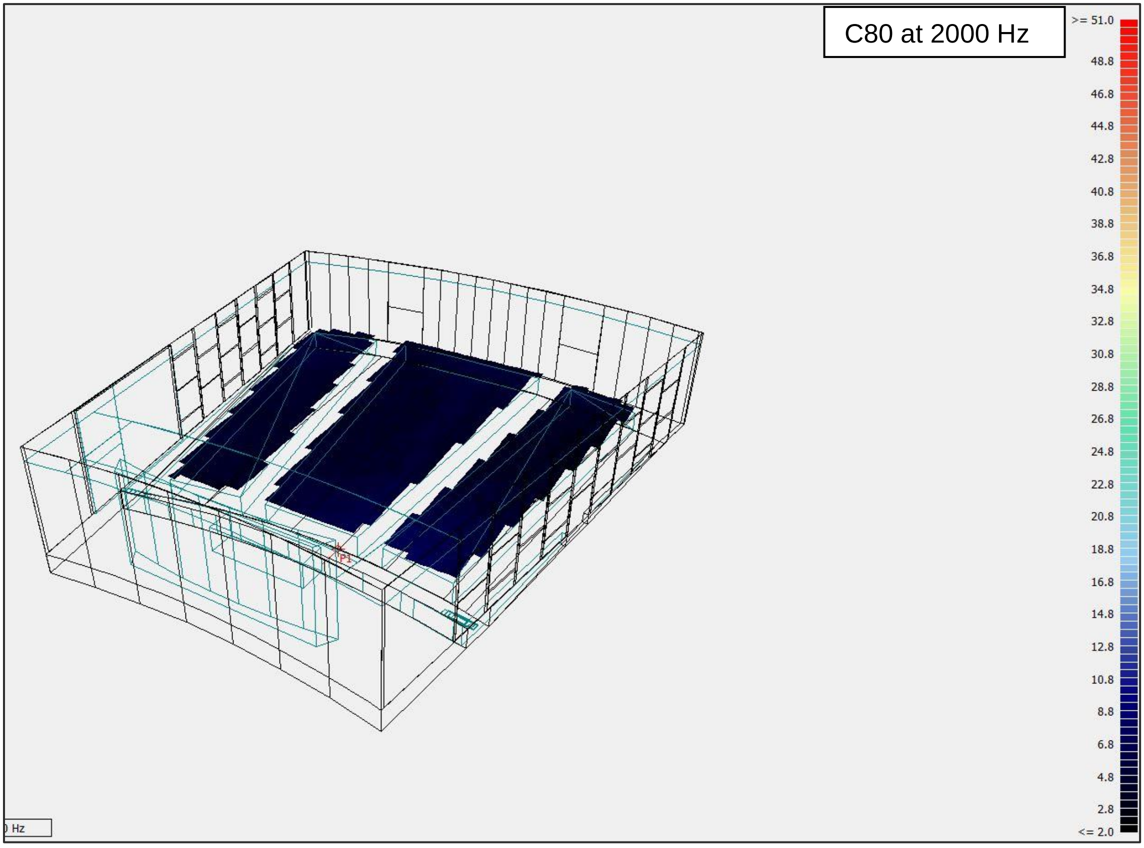
STI and RASTI

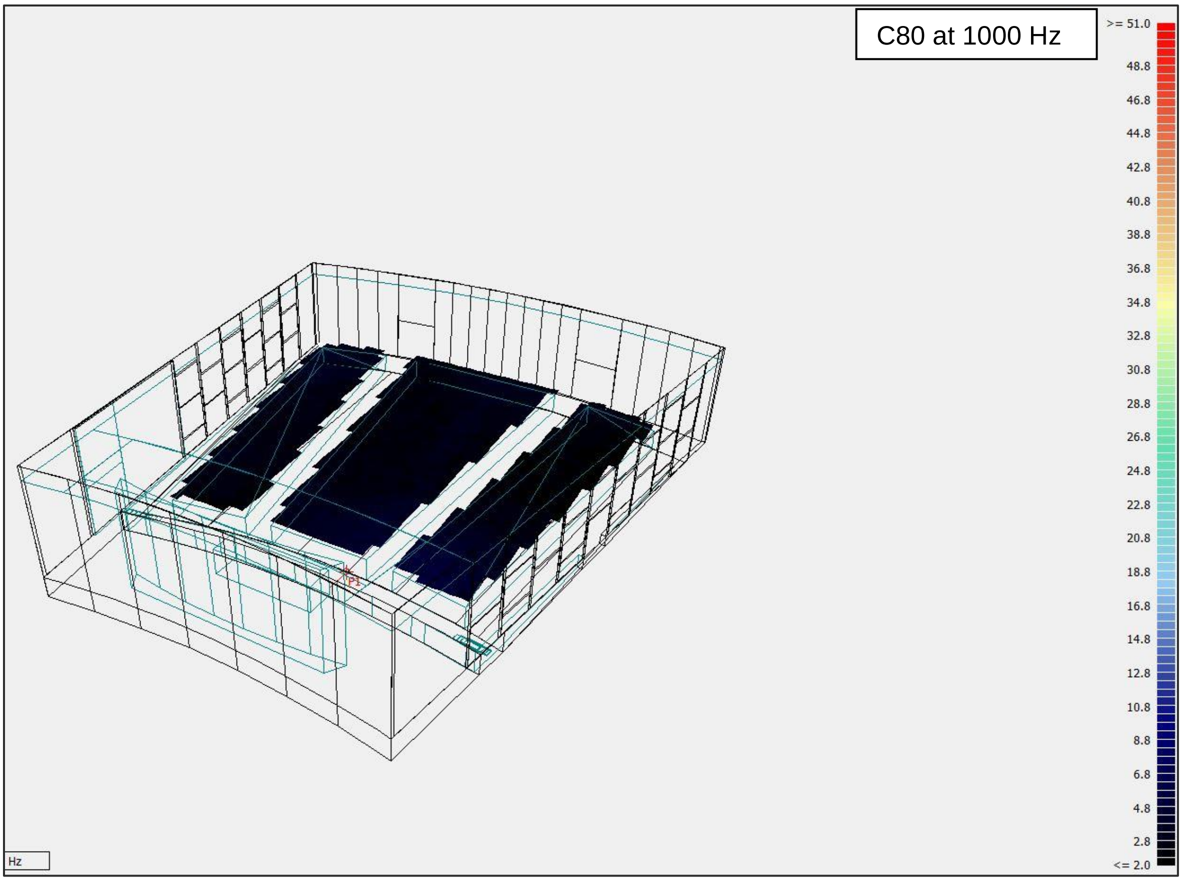
	RASTI	STI female	STI male
Pos 1	0.7	0.72	0.71
Pos 2	0.69	0.68	0.67
Pos 3	0.61	0.63	0.63
Pos 4	0.57	0.61	0.61
Pos 5	0.61	0.63	0.63
Pos 6	0.62	0.64	0.64
Pos 7	0.62	0.64	0.63
Pos 8	0.64	0.65	0.64
Pos 9	0.69	0.7	0.7
Pos 10	0.64	0.68	0.67
Pos 11	0.6	0.64	0.63
Pos 12	0.59	0.64	0.63
Pos 13	0.61	0.61	0.61
Pos 14	0.59	0.61	0.6
Pos 15	0.66	0.65	0.64
Pos 16	0.62	0.62	0.62
Pos 17	0.62	0.63	0.63
Pos 18	0.63	0.63	0.63
Pos 19	0.63	0.65	0.64
Pos 20	0.65	0.65	0.65
Pos 21	0.65	0.66	0.66

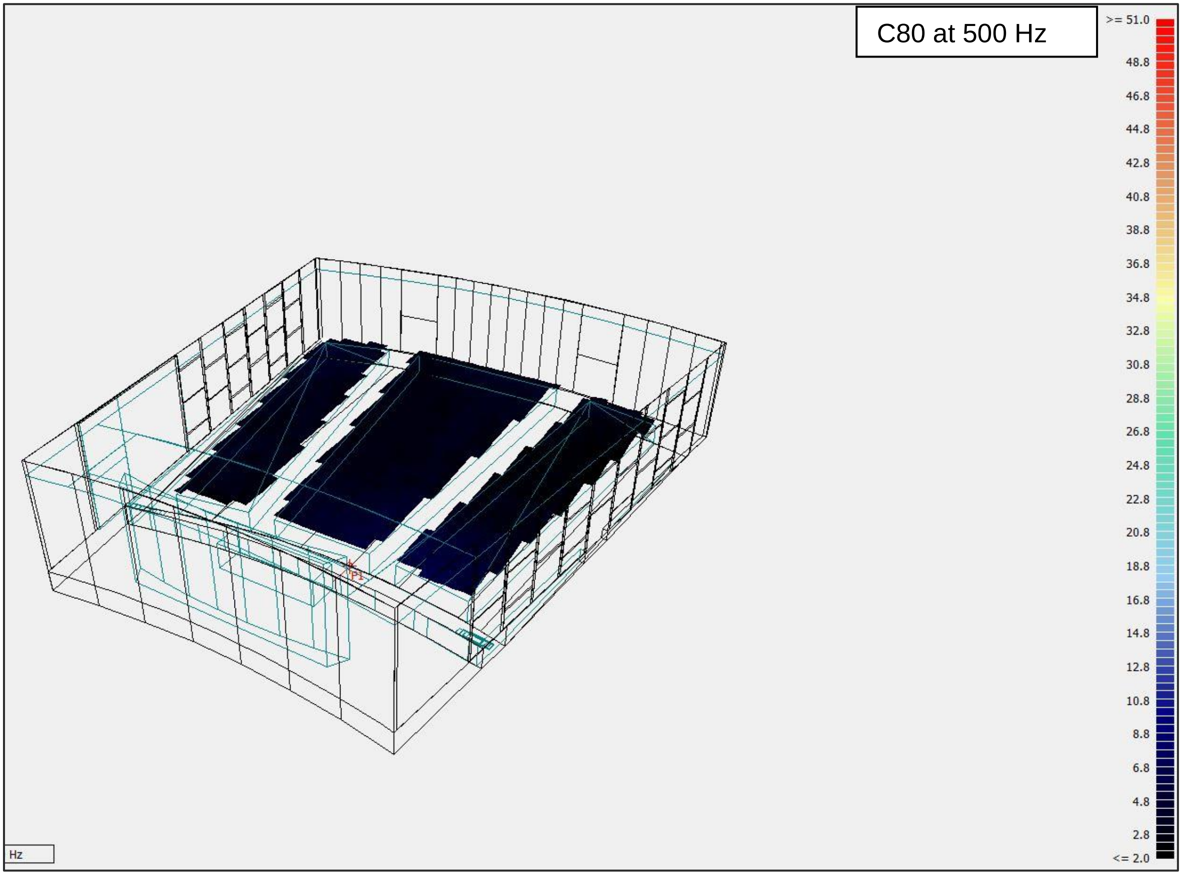
Annex 3 – Simulated acoustic parameters for the audience, 0% occupation

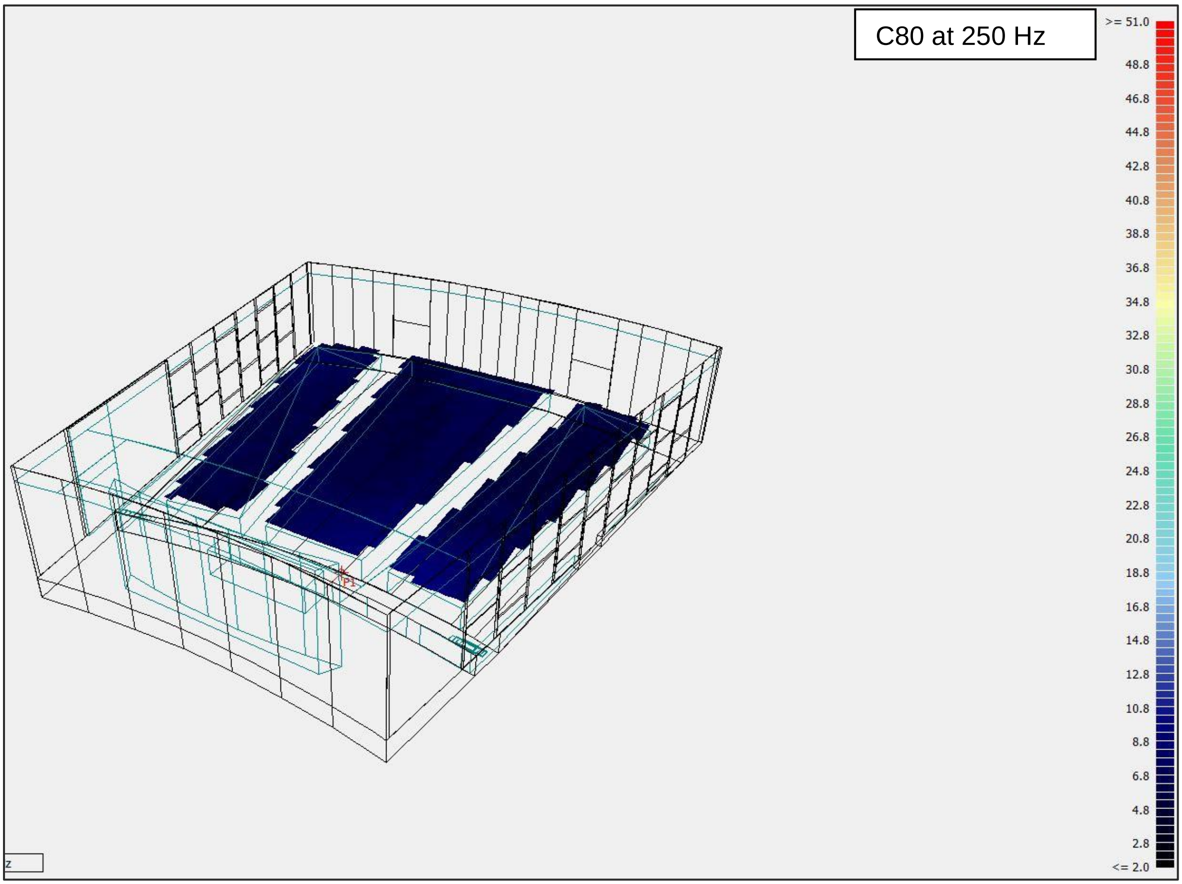
C80

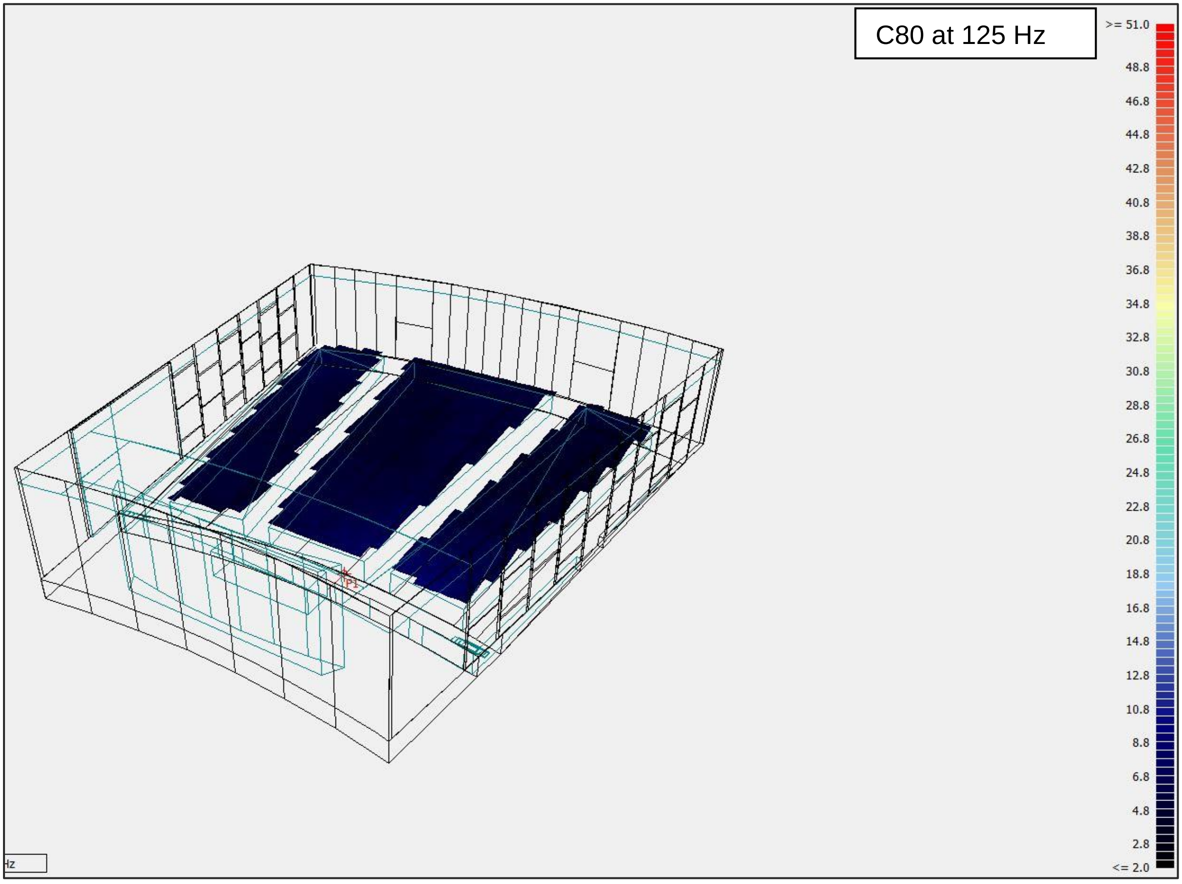




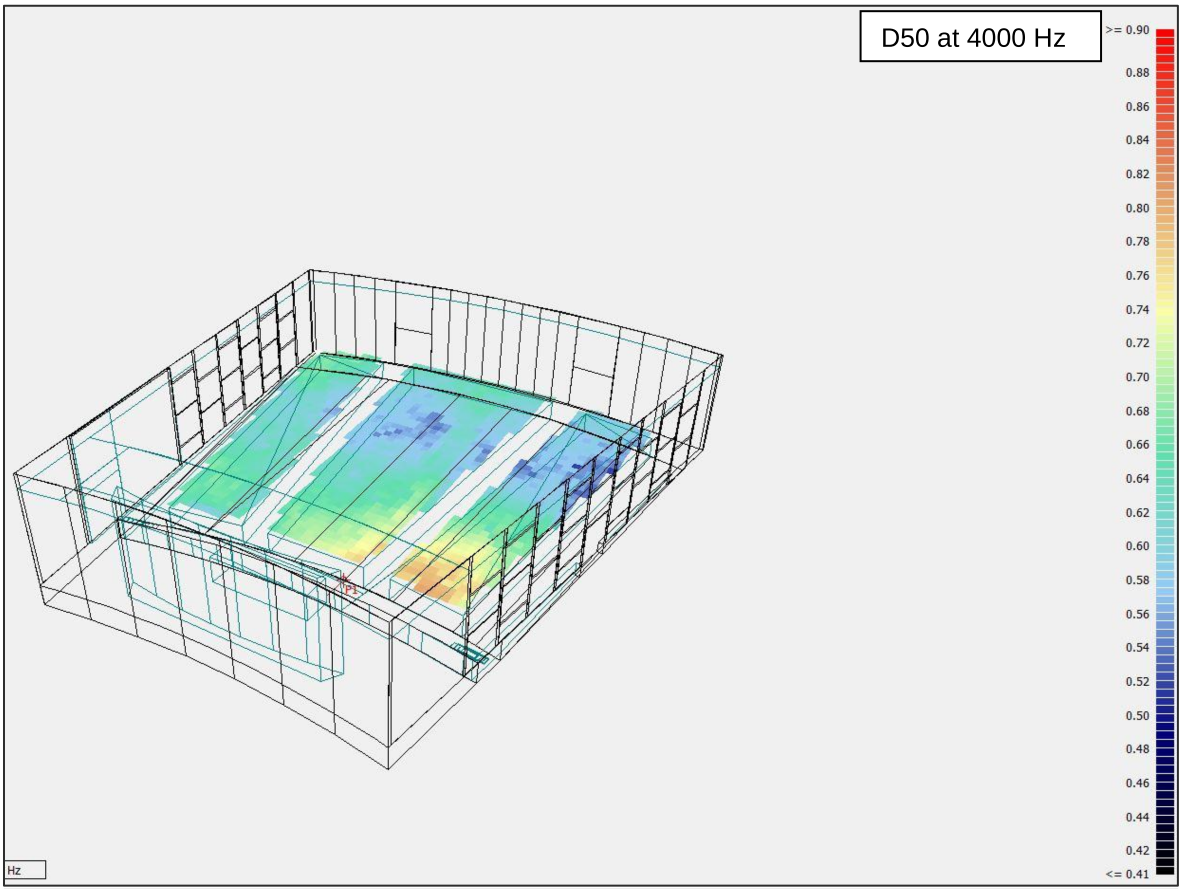

C80 at 1000 Hz
>= 51.0
48.8
46.8
44.8
42.8
40.8
38.8
36.8
34.8
32.8
30.8
28.8
26.8
24.8
22.8
20.8
18.8
16.8
14.8
12.8
10.8
8.8
6.8
4.8
2.8
<= 2.0
P1
Hz

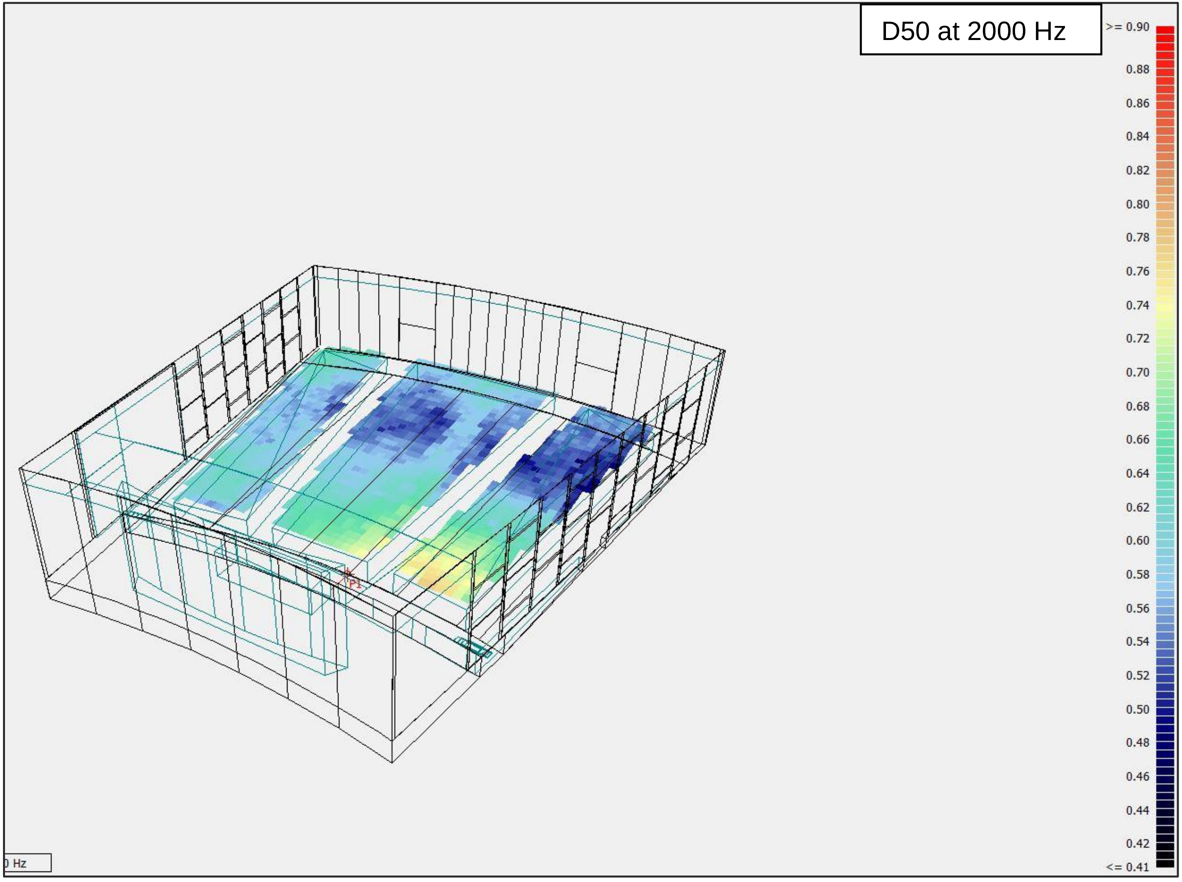

C80 at 500 Hz
>= 51.0
48.8
46.8
44.8
42.8
40.8
38.8
36.8
34.8
32.8
30.8
28.8
26.8
24.8
22.8
20.8
18.8
16.8
14.8
12.8
10.8
8.8
6.8
4.8
2.8
<= 2.0
P1
Hz

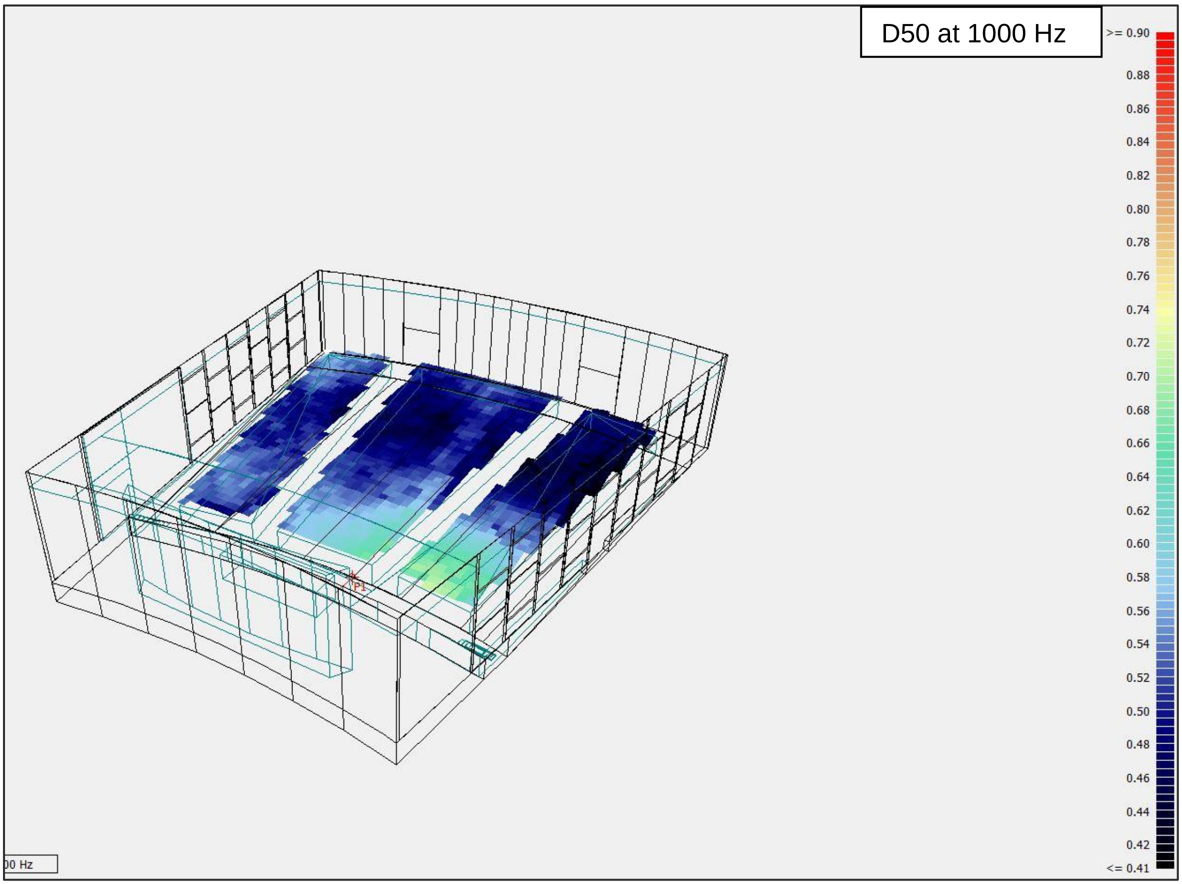

C80 at 250 Hz
>= 51.0
48.8
46.8
44.8
42.8
40.8
38.8
36.8
34.8
32.8
30.8
28.8
26.8
24.8
22.8
20.8
18.8
16.8
14.8
12.8
10.8
8.8
6.8
4.8
2.8
<= 2.0
P1
z


C80 at 125 Hz
>= 51.0
48.8
46.8
44.8
42.8
40.8
38.8
36.8
34.8
32.8
30.8
28.8
26.8
24.8
22.8
20.8
18.8
16.8
14.8
12.8
10.8
8.8
6.8
4.8
2.8
<= 2.0
P1
Hz

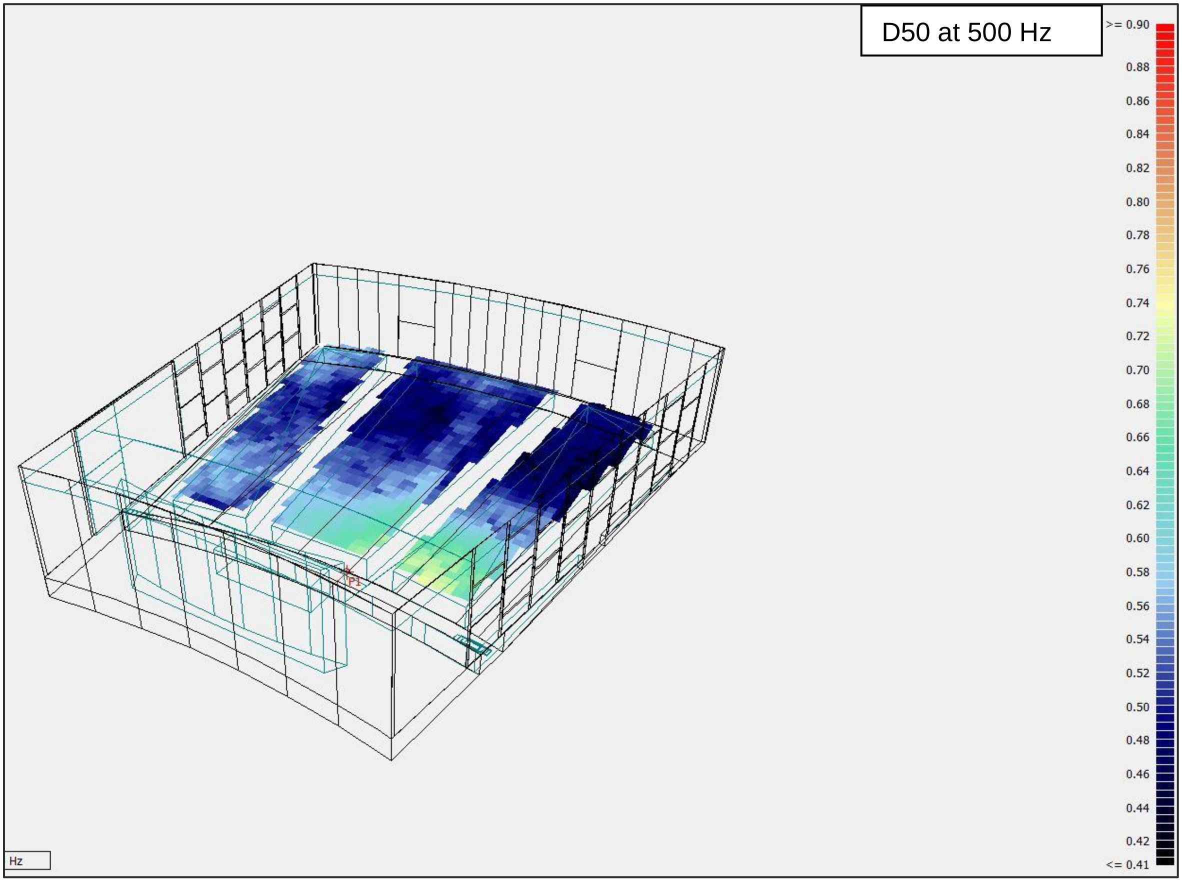
D50


D50 at 4000 Hz

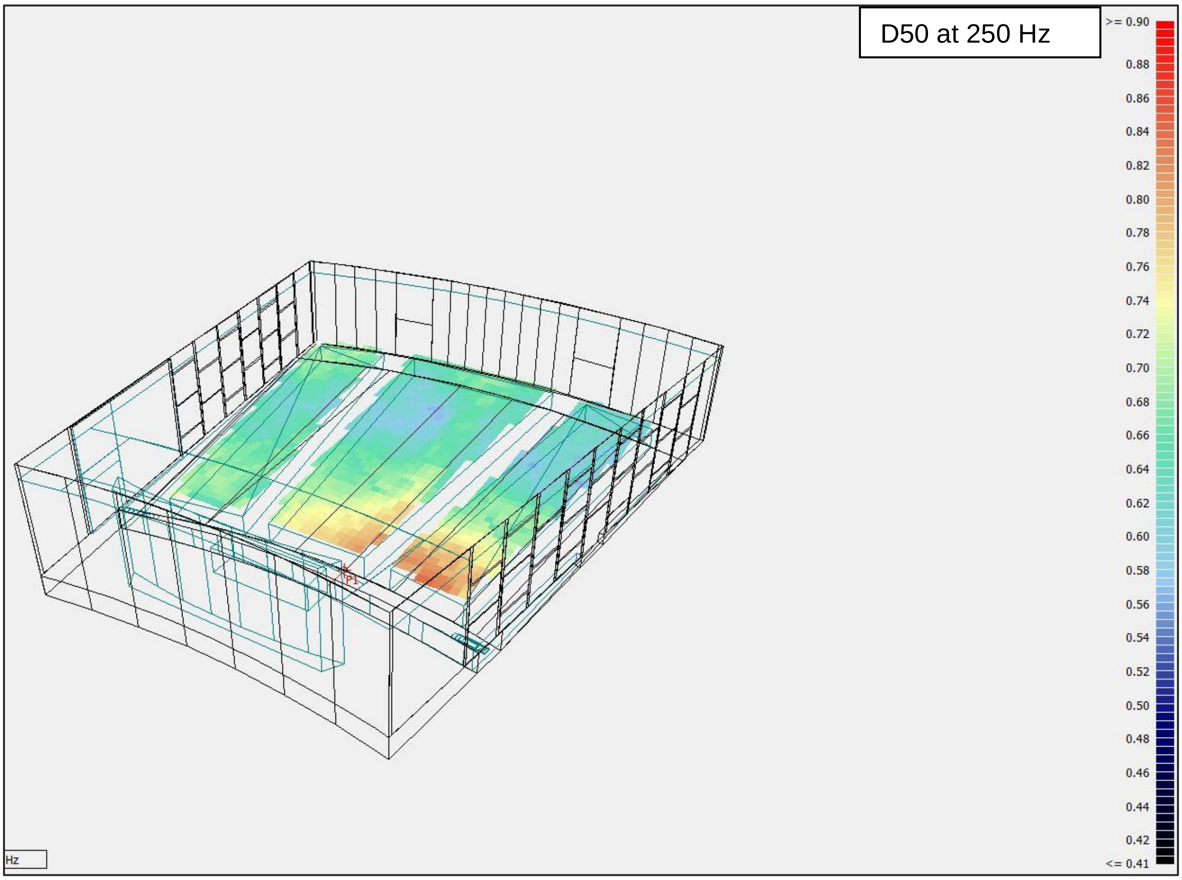

D50 at 2000 Hz



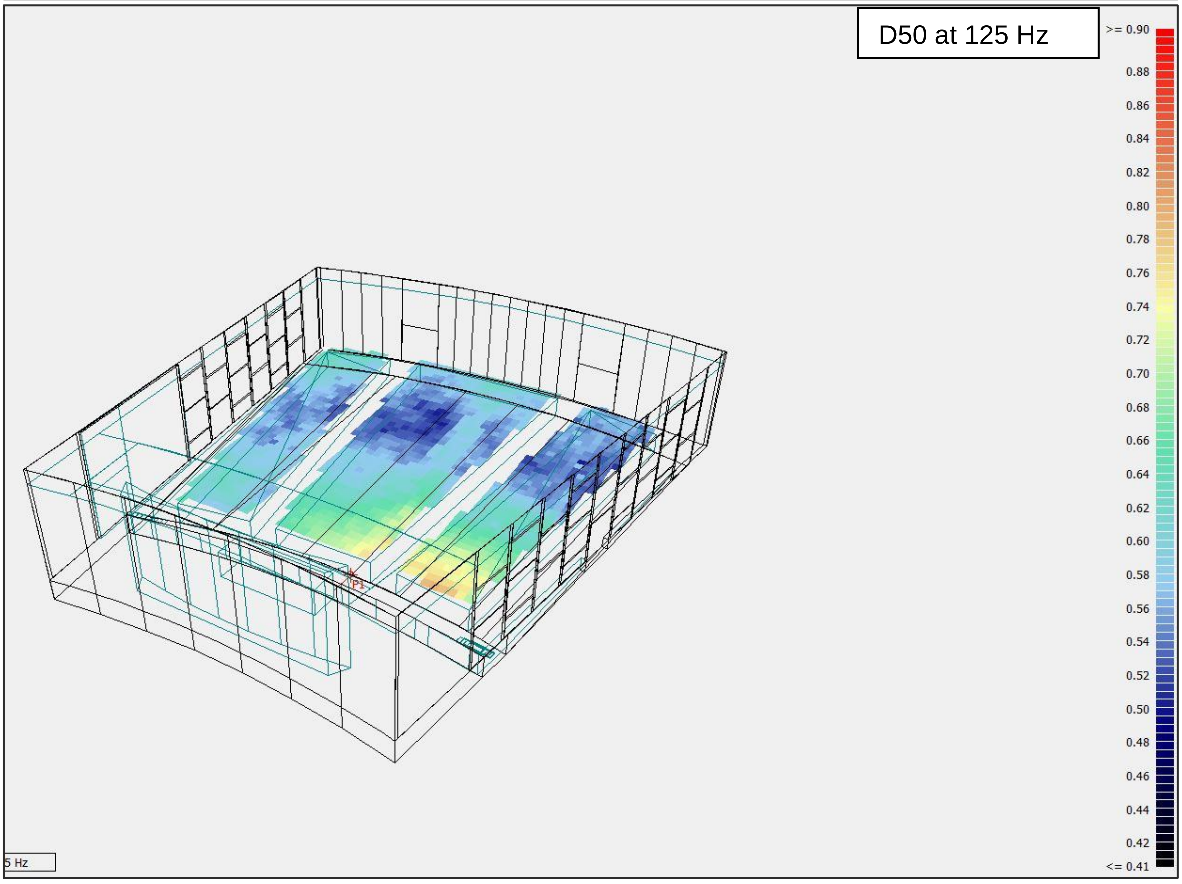
D50 at 1000 Hz



D50 at 500 Hz

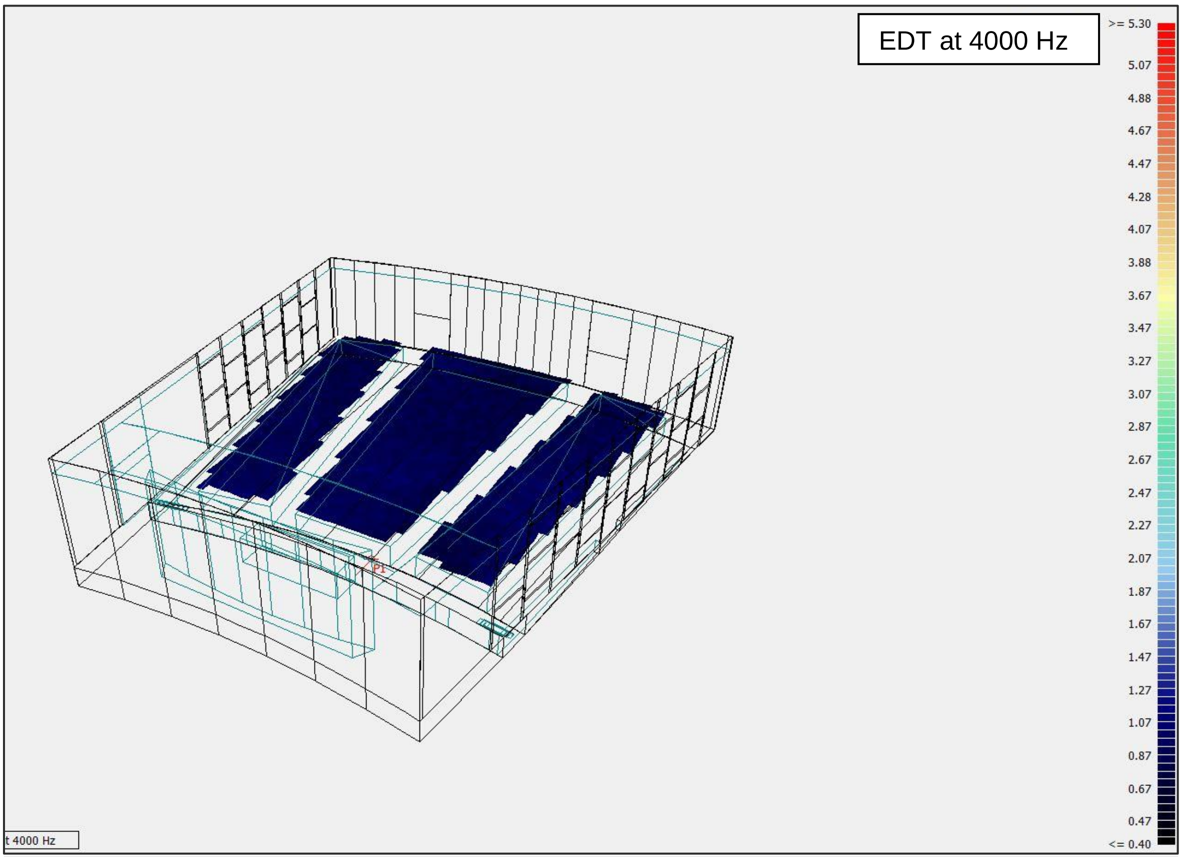


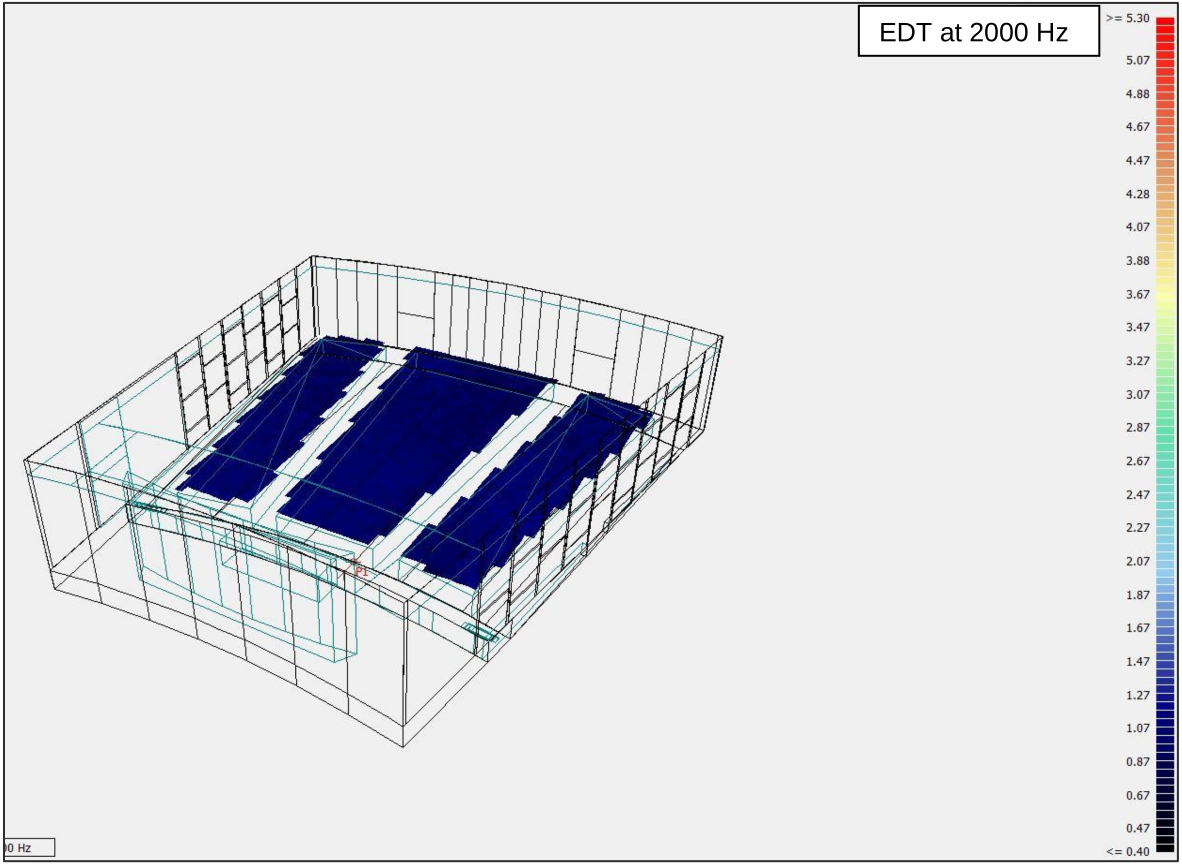
D50 at 250 Hz

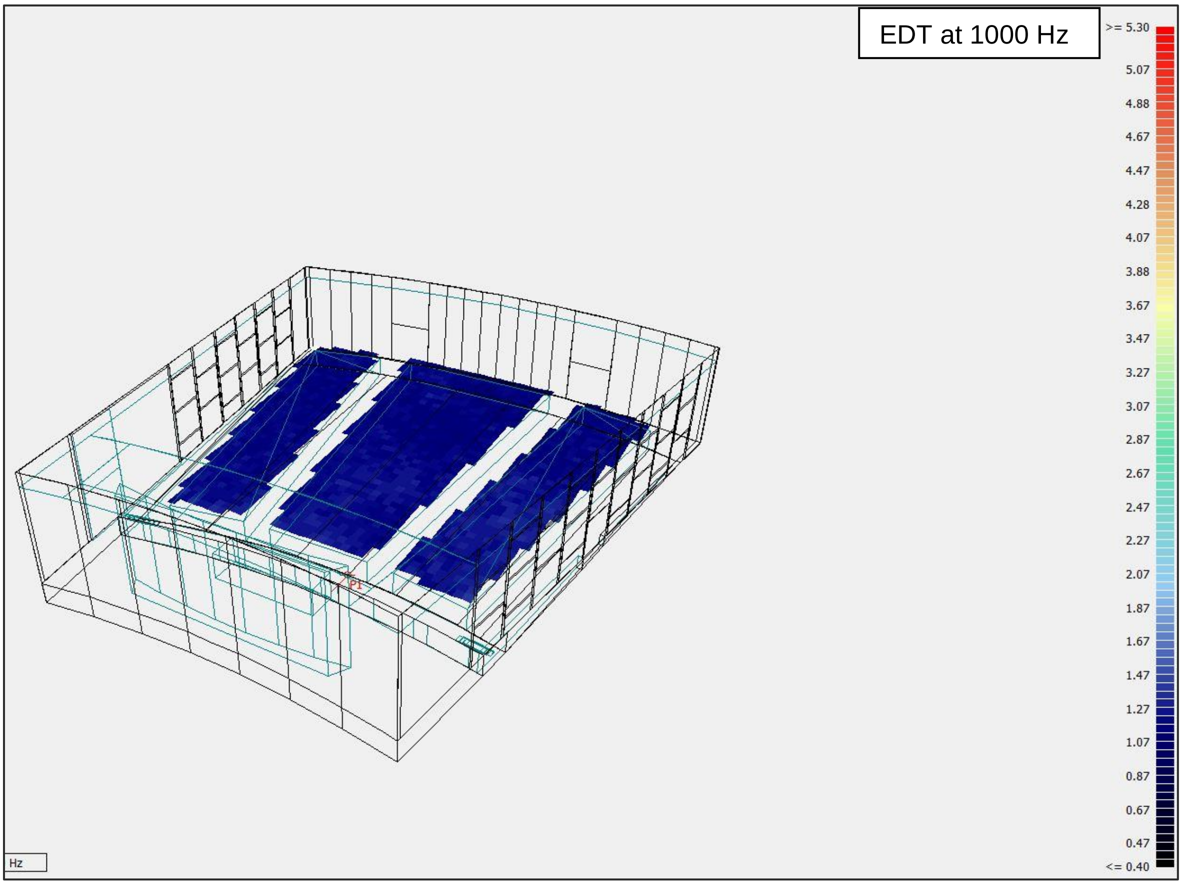


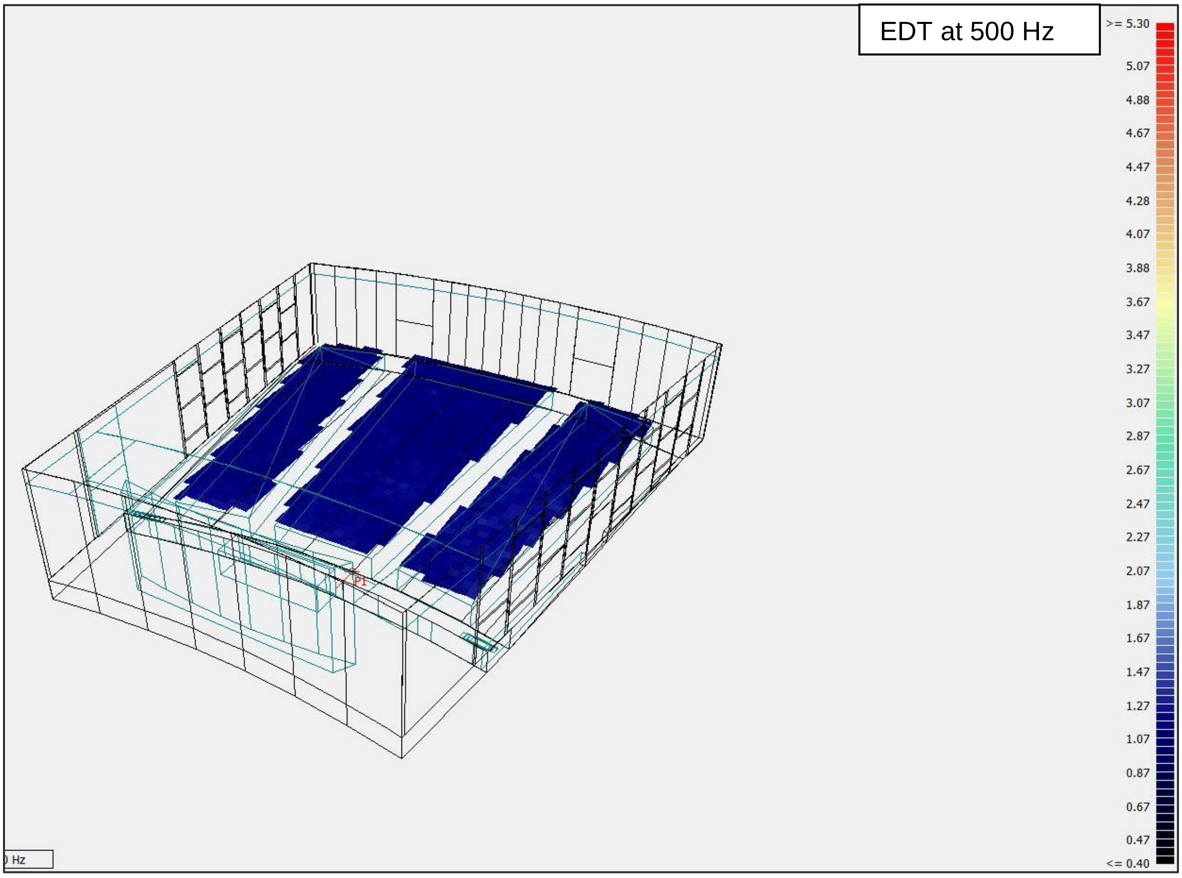
D50 at 125 Hz

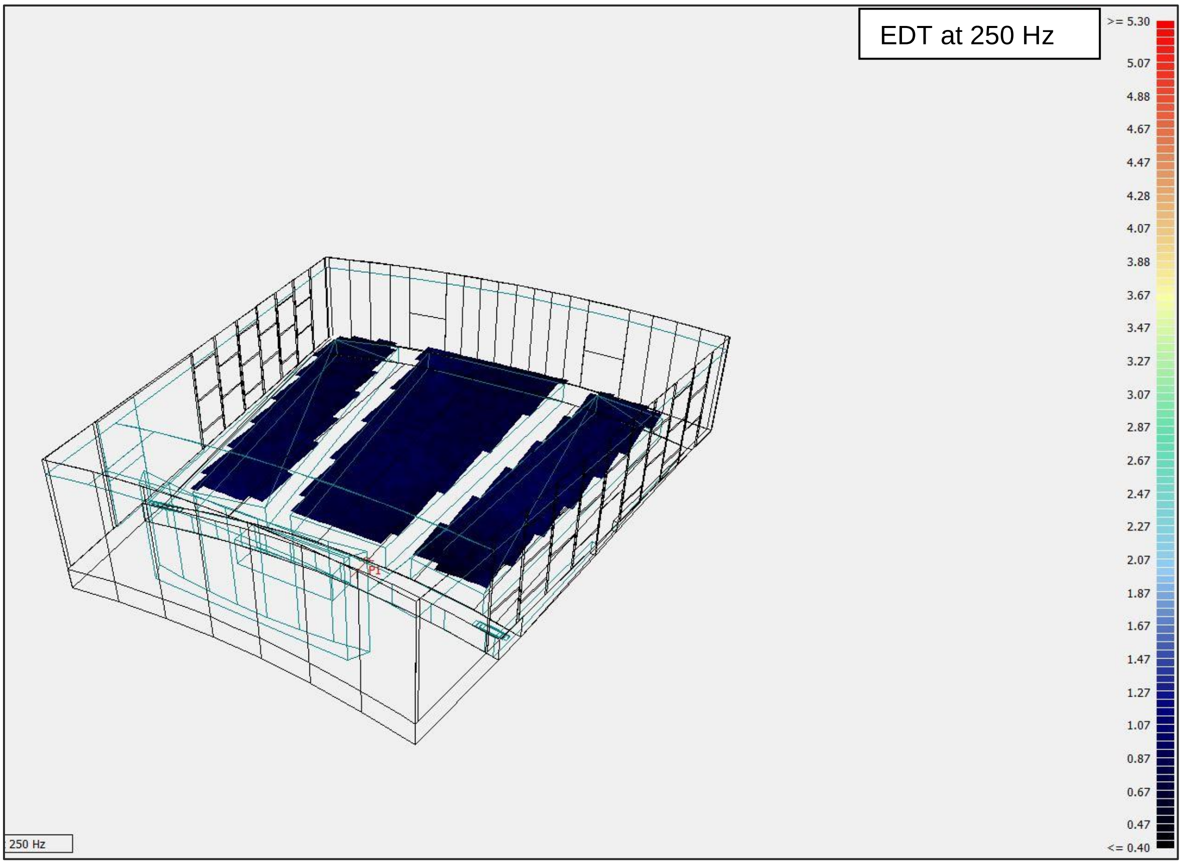
EDT

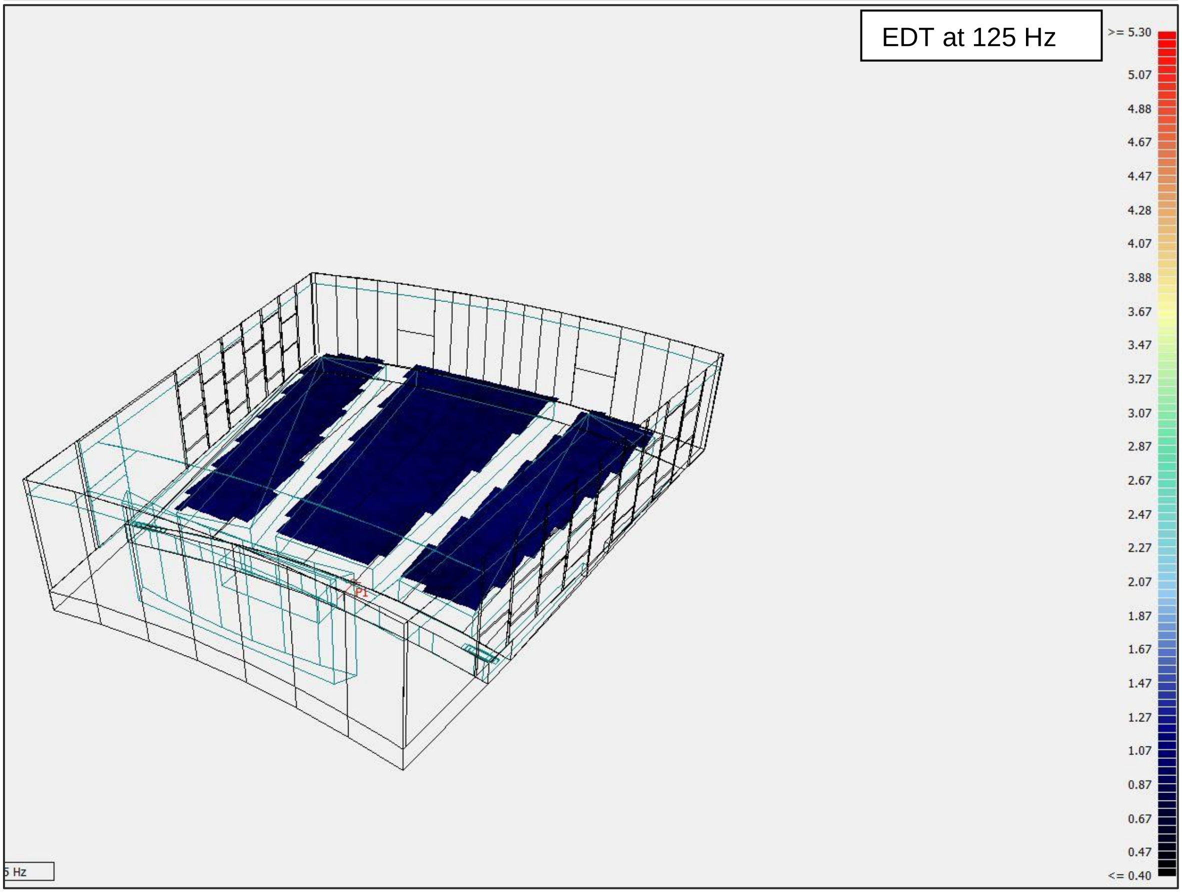

EDT at 4000 Hz
>= 5.30
5.07
4.88
4.67
4.47
4.28
4.07
3.88
3.67
3.47
3.27
3.07
2.87
2.67
2.47
2.27
2.07
1.87
1.67
1.47
1.27
1.07
0.87
0.67
0.47
<= 0.40
P1
t 4000 Hz


EDT at 2000 Hz
>= 5.30
5.07
4.88
4.67
4.47
4.28
4.07
3.88
3.67
3.47
3.27
3.07
2.87
2.67
2.47
2.27
2.07
1.87
1.67
1.47
1.27
1.07
0.87
0.67
0.47
<= 0.40
P1
)0 Hz

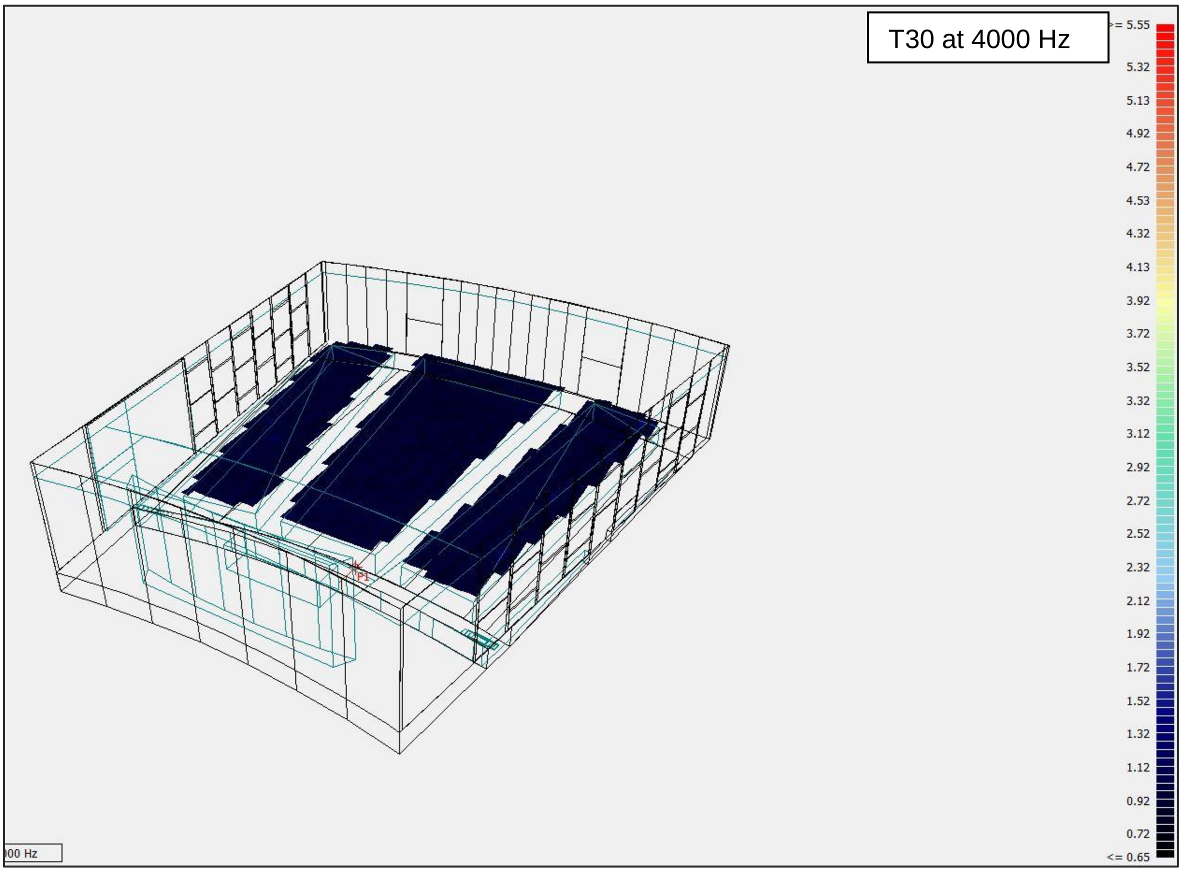

EDT at 1000 Hz
>= 5.30
5.07
4.88
4.67
4.47
4.28
4.07
3.88
3.67
3.47
3.27
3.07
2.87
2.67
2.47
2.27
2.07
1.87
1.67
1.47
1.27
1.07
0.87
0.67
0.47
<= 0.40
P1
Hz

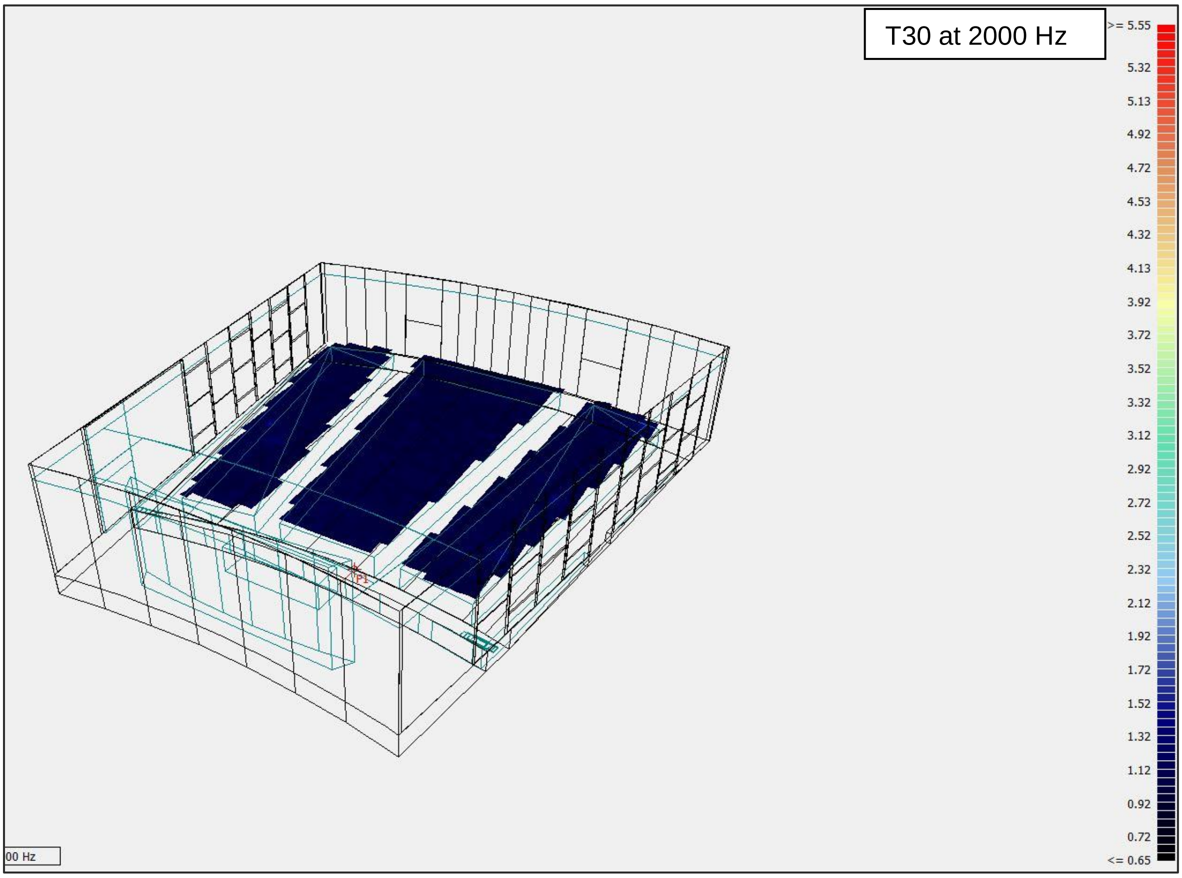

EDT at 500 Hz
>= 5.30
5.07
4.88
4.67
4.47
4.28
4.07
3.88
3.67
3.47
3.27
3.07
2.87
2.67
2.47
2.27
2.07
1.87
1.67
1.47
1.27
1.07
0.87
0.67
0.47
<= 0.40
P1
Hz

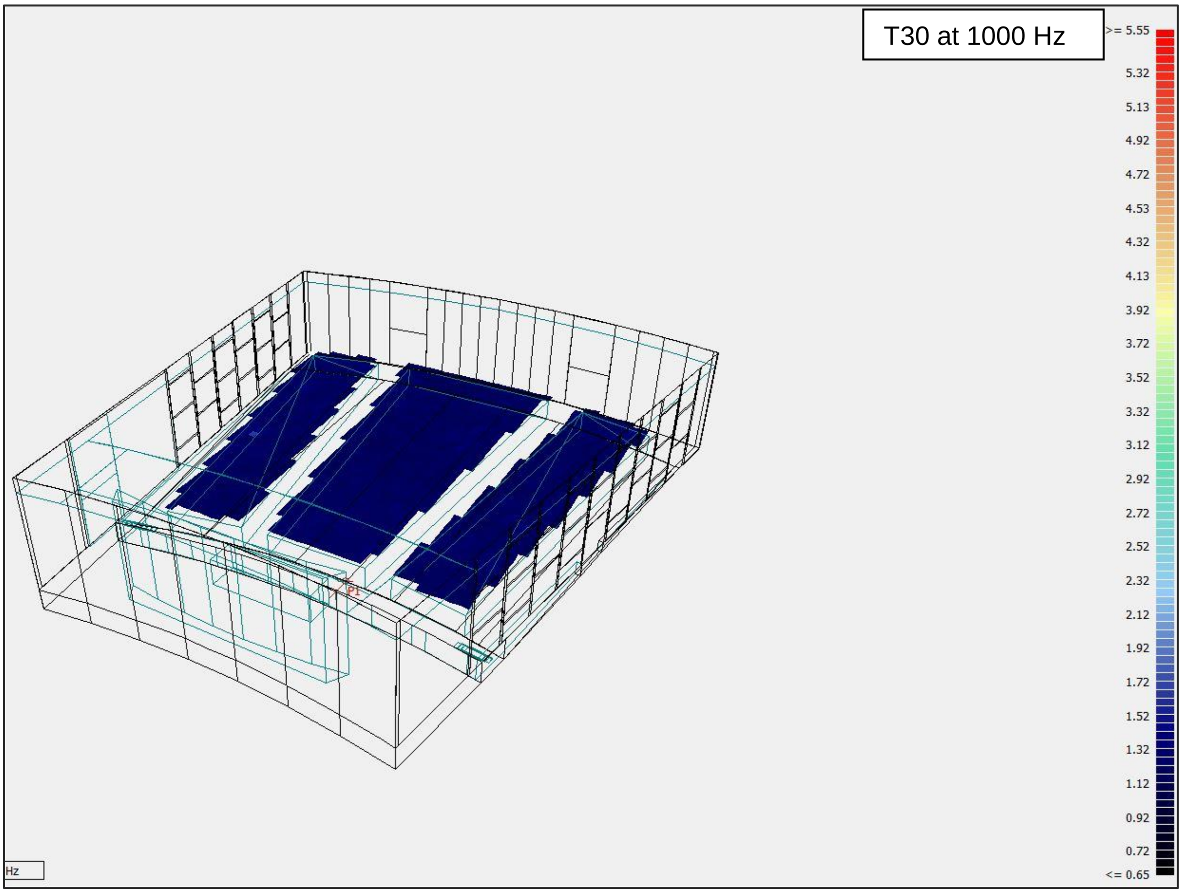

EDT at 250 Hz
>= 5.30
5.07
4.88
4.67
4.47
4.28
4.07
3.88
3.67
3.47
3.27
3.07
2.87
2.67
2.47
2.27
2.07
1.87
1.67
1.47
1.27
1.07
0.87
0.67
0.47
<= 0.40
P1
250 Hz

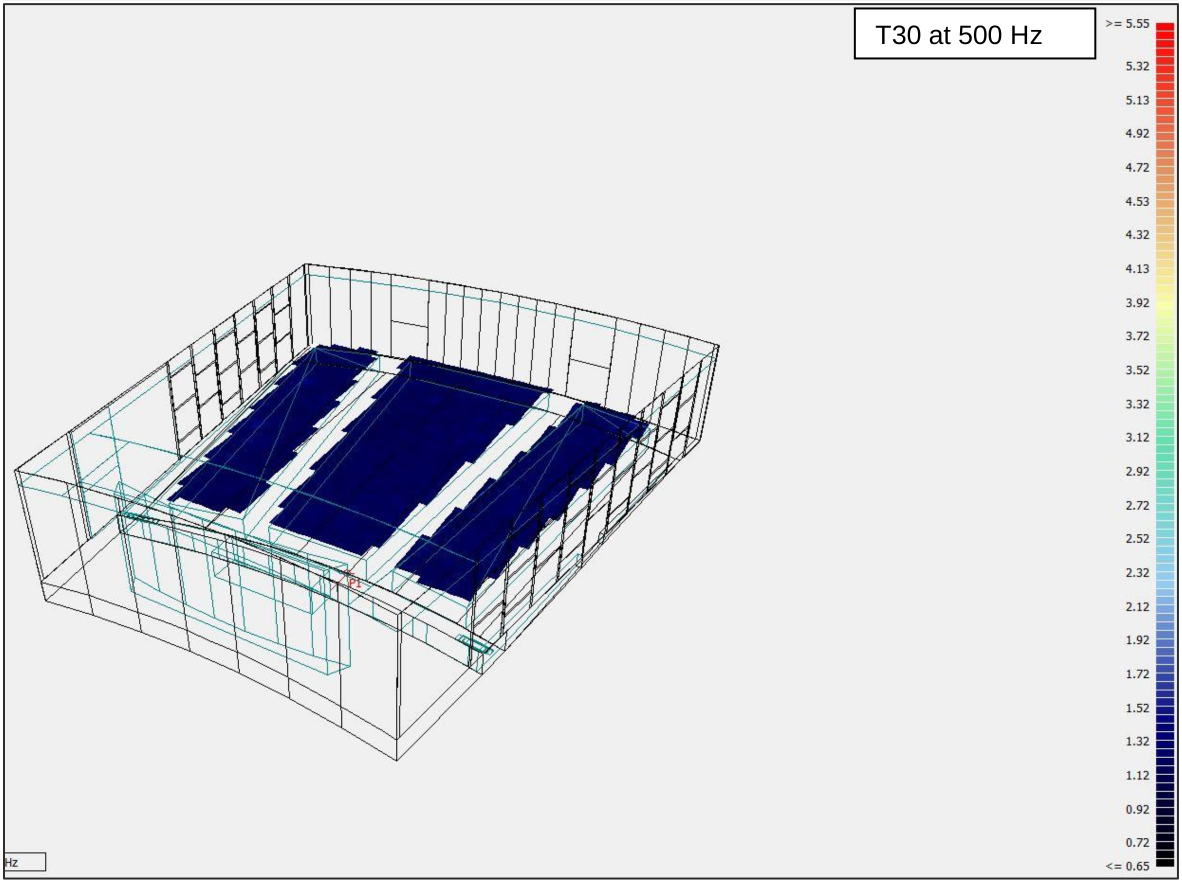

EDT at 125 Hz
>= 5.30
5.07
4.88
4.67
4.47
4.28
4.07
3.88
3.67
3.47
3.27
3.07
2.87
2.67
2.47
2.27
2.07
1.87
1.67
1.47
1.27
1.07
0.87
0.67
0.47
<= 0.40
P1
5 Hz

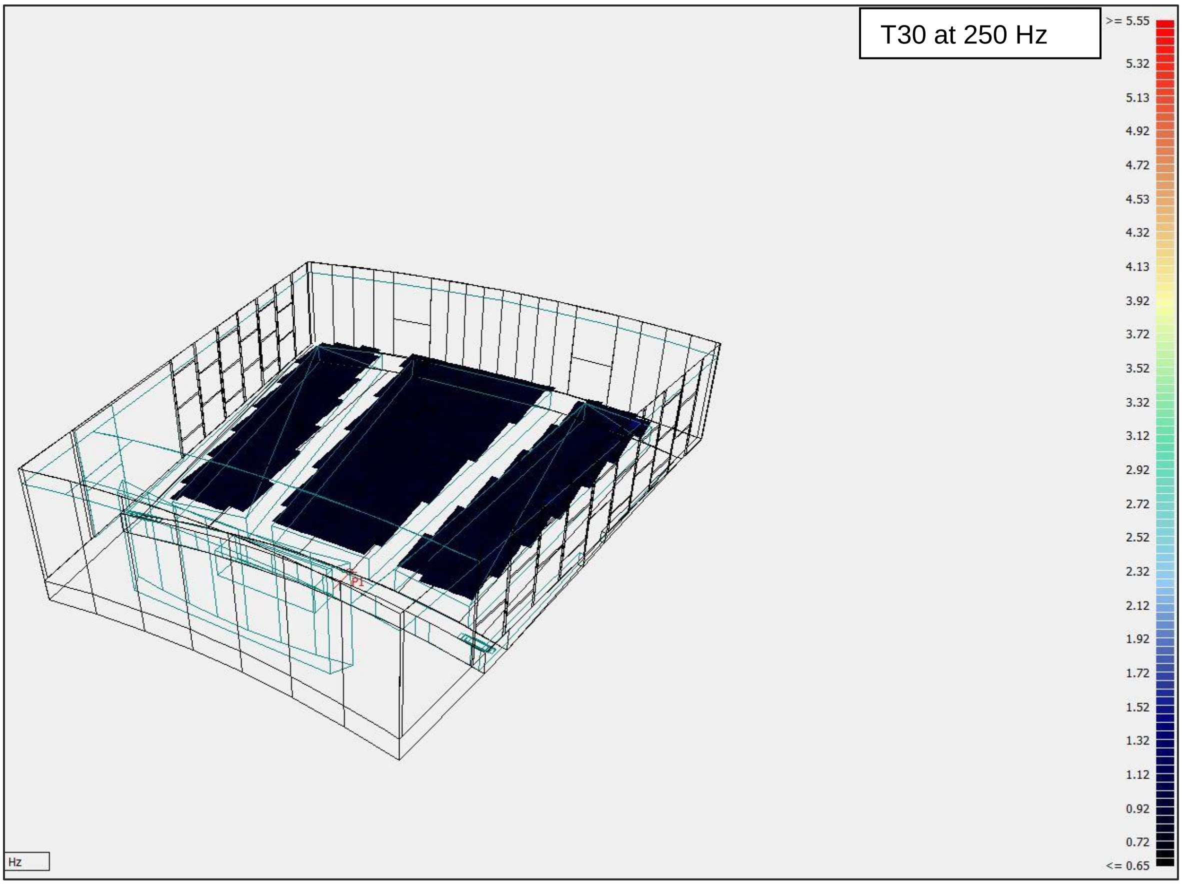
T30


T30 at 4000 Hz
>= 5.55
5.32
5.13
4.92
4.72
4.53
4.32
4.13
3.92
3.72
3.52
3.32
3.12
2.92
2.72
2.52
2.32
2.12
1.92
1.72
1.52
1.32
1.12
0.92
0.72
<= 0.65
P1
00 Hz

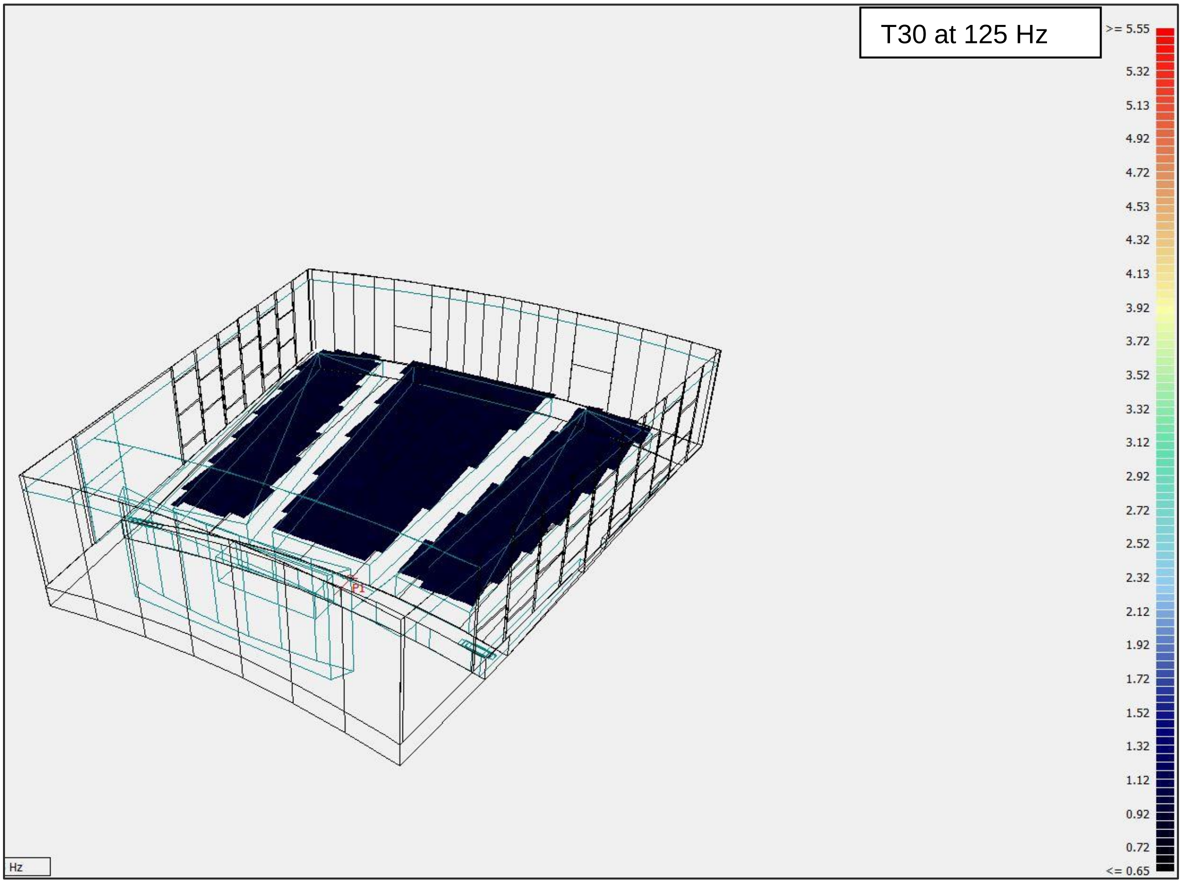

T30 at 2000 Hz
>= 5.55
5.32
5.13
4.92
4.72
4.53
4.32
4.13
3.92
3.72
3.52
3.32
3.12
2.92
2.72
2.52
2.32
2.12
1.92
1.72
1.52
1.32
1.12
0.92
0.72
<= 0.65
P1
00 Hz


T30 at 1000 Hz


T30 at 500 Hz

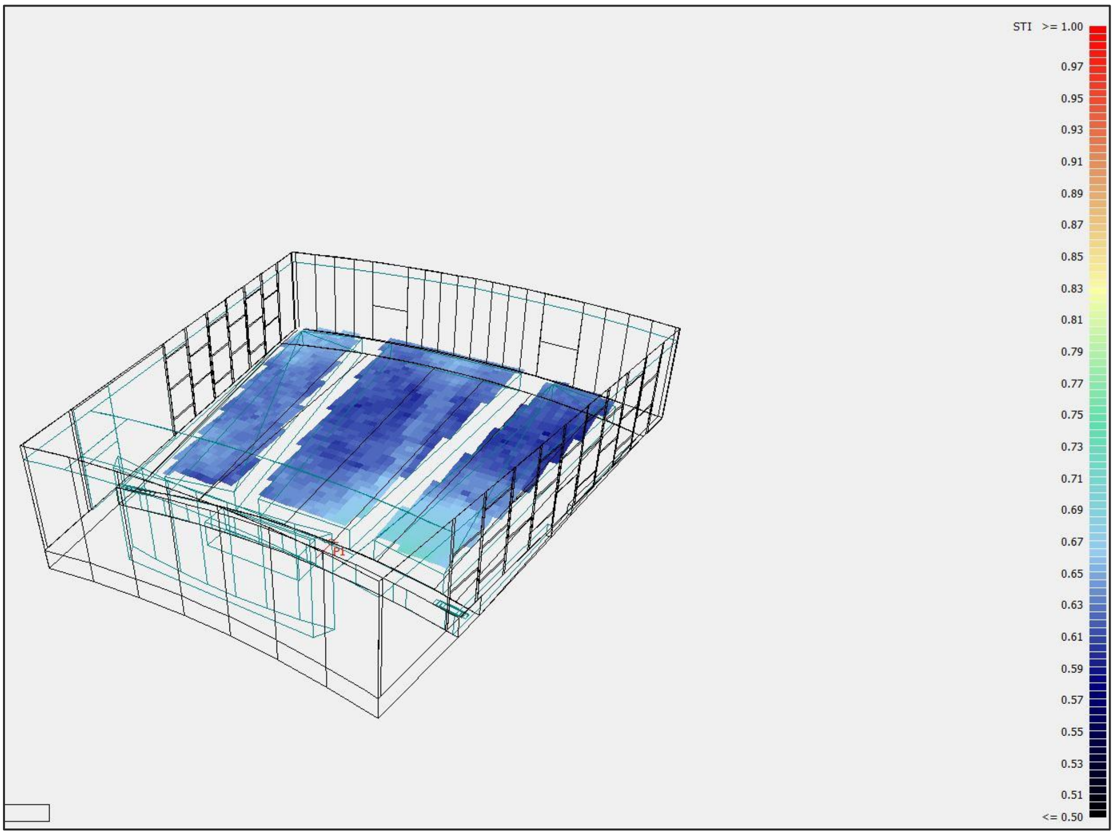


T30 at 250 Hz

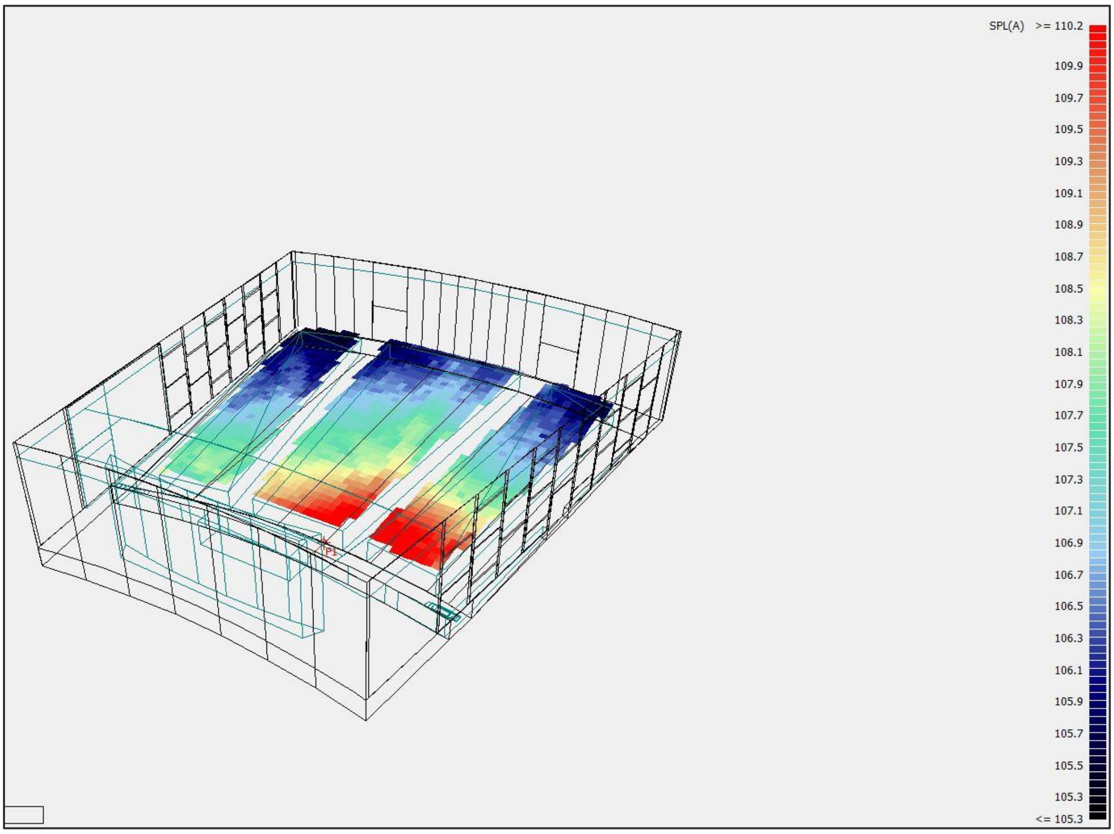


T30 at 125 Hz

STI


STI >= 1.00
0.97
0.95
0.93
0.91
0.89
0.87
0.85
0.83
0.81
0.79
0.77
0.75
0.73
0.71
0.69
0.67
0.65
0.63
0.61
0.59
0.57
0.55
0.53
0.51
<= 0.50
P1

SPL


SPL(A) >= 110.2
109.9
109.7
109.5
109.3
109.1
108.9
108.7
108.5
108.3
108.1
107.9
107.7
107.5
107.3
107.1
106.9
106.7
106.5
106.3
106.1
105.9
105.7
105.5
105.3
<= 105.3
P1